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An Examination of Man Made Radio Noise at 37 HF Receiving Sites

by

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13. ABSTRACT *(maximum 200 words)* Man-made radio noise has been examined at 37 HF receiving sites spaced at wide intervals around the world. The measurements were made with the goal of understanding the temporal and spectral structure of each example of man-made noise, determining the sources involved, and developing procedures to minimize the impact of man-made noise on signal reception. All measurements were made at the input terminals of receivers at each site as contrasted to the more traditional field-strength measurement of radio noise collected by a monopole antenna. The results obtained from all of the sites were summarized, tabulated, and related to sources. The results were also compared with the ITU model for man-made noise. The measured results did not agree with the categories of noise used in the ITU model, and they often varied from the 1/f aspects of the model. The results suggest the need for a new model based on the number of electric-utility-power poles that are located within line of sight of the uppermost part of the antennas at each receiving site.

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INTRODUCTION

Man-made radio noise appearing at the input terminals of receivers at a large number of high-frequency (HF) receiving sites has been examined, and this document presents a summary of the results obtained from thirty-seven widely-separated HF sites. The task was conducted over a period of more than two decades. The objectives were to: (a) better understand the impact of man-made radio noise on the reception of HF signals, (b) obtain information about the sources of man-made noise, and (c) devise methods and implement actions to minimize the noise. Instrumentation was used at each site that provided detailed information about the temporal and spectral structure of each case of man-made noise appearing at the input terminals of the receivers. Such information allowed operators of the instrumentation to assess the adverse effect of man-made noise on the reception of various types of HF signals and identify the source of each individual noise. In most cases the dominant noise was determined to be from sources on overhead distribution lines which distribute electric power from substations to customers.

INSTRUMENTATION

Figure 1 shows a block diagram of the measurement instrumentation. It usually consisted of a bank of band-pass filters, used one at a time, to limit the total signal and noise power into the preamplifier and the spectrum analyzer to low enough levels to avoid saturation and the deleterious effects of nonlinear operation. For some measurements at locations encountering unusually high-level signals in the International Broadcast Service bands a narrow-band pre-selector was used in place of the filter bank. A high dynamic range preamplifier was used to obtain a system signal- and noise-detection sensitivity about equal to that of a standard HF receiver. A spectrum analyzer (HP-141) was used as a scanning or fixed-tuned receiver to observe signals and noise within the pass band of each filter. A time-history display (ELF Engineering Inc. Model 7200B) was used to portray a succession of 60 analyzer scans in a 3-axis format and provide the operator with a visual view of all signals and noise in the band under observation. An oscilloscope camera (Tektronix Model C-5C) was used to photograph any desired time-history view. The instrumentation is described in more detail in another publication[1].

Peak and average noise-power measurements were made within a stated gaussian-shaped bandwidth at the 50-Ohm impedance of the signal-distribution system at each site. All measurements were made from the antennas used by the receivers at each site.

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[1] Wilbur R. Vincent and George F. Munsch, ***Power-Line Noise Mitigation Handbook for Naval and other Receiving Sites***, 5th edition, Report No. NPS-EC-02-002, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, January 2002

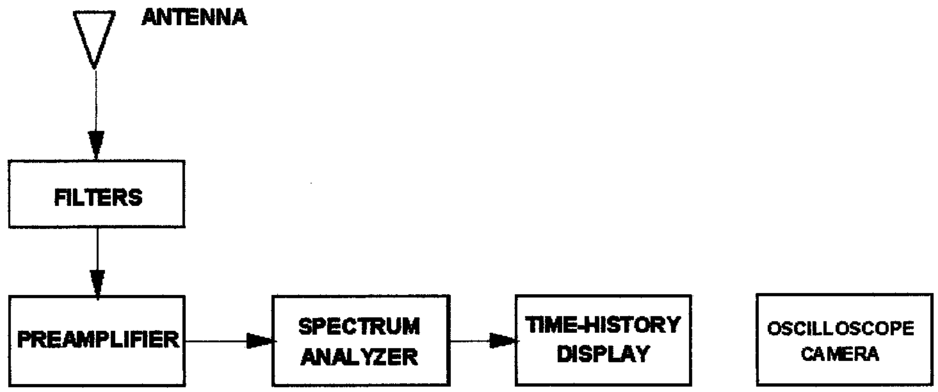


Figure 1

Block Diagram of the Instrumentation

All examples of data collected at all sites were fully calibrated in frequency, amplitude, and time. A small table accompanies each example of data collected by the instrumentation to record key test parameters. The information in this table is:

Line 1	Local time in 24 hr. format, date in yymmdd format
Line 2	Site identification, antenna identification, antenna direction
Line 3	Center frequency, scan width, IF bandwidth, scan time*
Line 4	Filter, preamplifier gain, RF attenuation, IF gain
Line 5	Additional information

* (LS) is appended when line synchronization is used.

EXAMPLES OF DATA

Figure 2 shows a typical example of the kind of information provided to the instrumentation operator in real time at each receiving site. A pair of views of the same data is produced by the instrumentation. The upper view of Figure 2 shows the coarse-scale spectral structure of one example of man-made noise covering the frequency range from less than 1 MHz up to 100 MHz. The lower view shows signals and noise received over 60 successive scans of the spectrum analyzer where the amplitude is severely, but not completely, compressed. The scan time of the analyzer is adjusted to receive multiple wide-band noise impulses during each scan. The slanting lines in the time-history view of the same data result from the interaction between the slow scanning process of the spectrum analyzer and the faster repetitive occurrence of the impulsive noise. Both narrow-band signals and broadband noise are shown in the pair of views. The type of information shown (along with additional information obtained from fine-scale views of the noise structure) is highly useful in assessing the impact of various kinds of noise on the reception of signals and to determine the properties of noise present at the input terminals of a receiver.

The time-history view of Figure 2 shows the noise is from a source that is erratic in operation. This is typical of many sources of man-made noise. The time-varying operation and the variety of spectral and temporal structures of noise produced by various sources complicate the task of providing simple descriptions of such noise. In the example shown, the activity changes about half way up the time scale. The amplitude is fairly constant across the HF band (for noise activity shown in the lower portion of the time-history view), but it then increases in amplitude up to about 80 MHz. Significant narrow peaks and nulls in the amplitude of noise along the frequency axis complicate the measurement of amplitude, but the peak amplitude of the noise and the general spectral structure is presented as are the gross temporal variations.

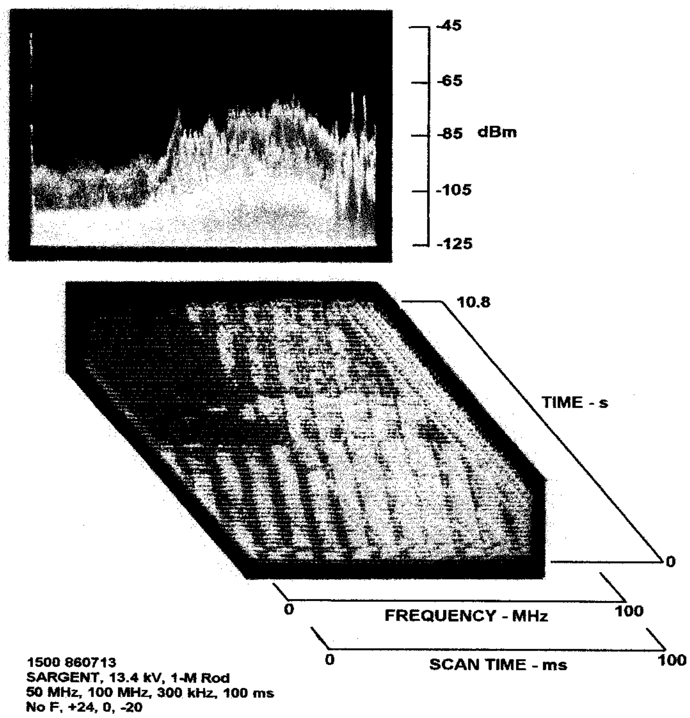


Figure 2

Example of the Coarse-Scale Spectral and Temporal Structure of Man-made Radio Noise

Figure 3 shows the fine-scale temporal structure of noise emanating from a frequently observed type of source. In this case the frequency-scanning process was set at zero with the spectrum analyzer frequency control set to 2.5 MHz. The scan process of the analyzer was synchronized to the frequency of the power source for this example. With these settings the output data is similar to the presentation on an oscilloscope operating in its line-sync mode. The noise consists of groups of close-spaced impulses which occur every 8.3 ms, one half the period of the power-line frequency. The uniform amplitude of each impulse is shown in the upper view, and the distinctive temporal pattern of the impulses in each group is shown in the lower view. The unique temporal pattern of this example identifies the most likely source of the noise as a bell insulator on a nearby overhead distribution line. The signatures of many other sources of noise are illustrated and described in Reference 1.

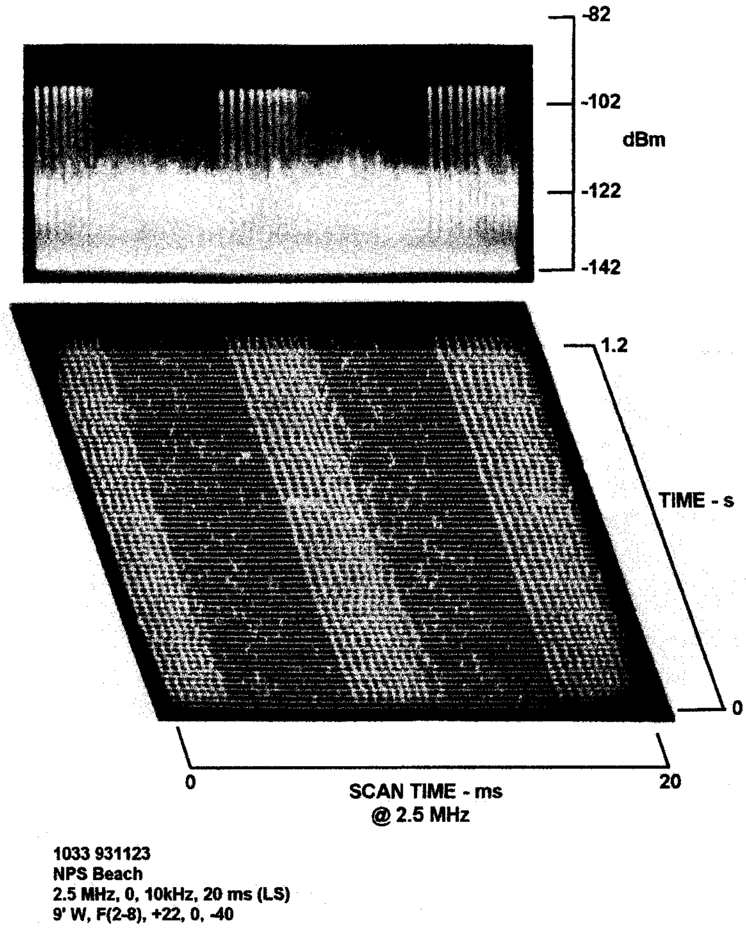
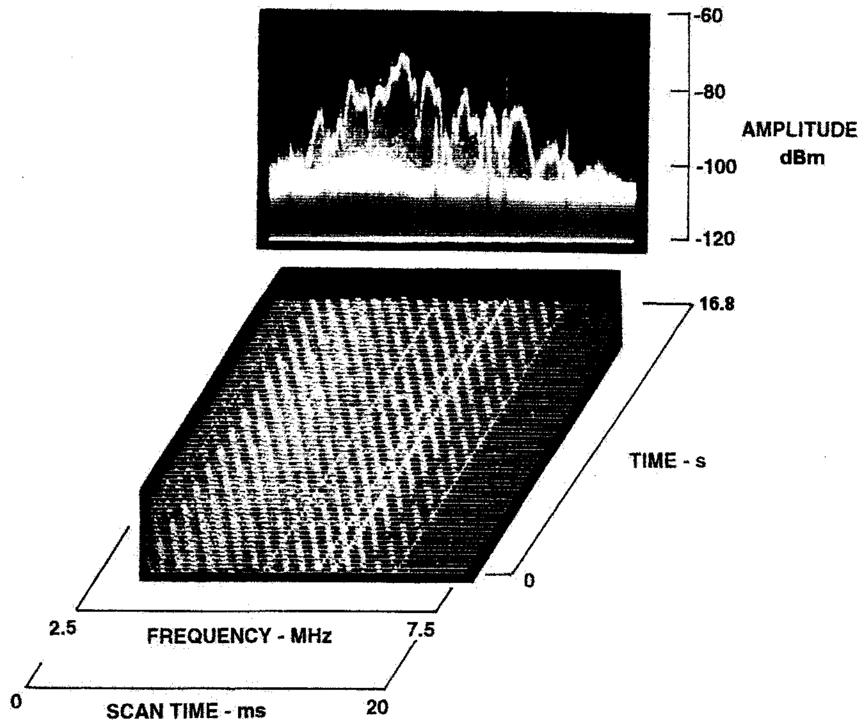


Figure 3

Example of the Fine-Scale Temporal Structure of Man-Made Radio Noise

One additional example is provided to illustrate the difficulty in establishing a value for the amplitude of noise. Figure 4 shows a typical view of fine-scale variations in the spectral content of man-made radio noise. Significant peaks and nulls in amplitude as frequency is changed are shown. Care was taken to ensure that the entire measurement system was flat in frequency response to avoid instrumentation distortion of the spectral content of noise. The reason for the peaks and nulls is attributed to the resonant properties of the radiation mechanism associated with the source; in this case the conductors of an overhead power line. Because of the peaks and nulls the amplitude of man-made noise measured at one frequency rarely provides good information about its amplitude at another nearby frequency or at any other frequency.



911203 1050
SS, A-240
5 MHz, 5 MHz, 10kHz, 200 ms
LPF 1, +20, -10, -20

Figure 4
Fine-Scale Variations in Amplitude

Massive amounts of data in the form shown in Figures 2 through 4 were accumulated at each receiving site and the data was recorded in notebooks. The data was extensively used in near real time to identify each source of noise as well as to provide a permanent record. When one or more cases of noise occurred simultaneously, the two views of the same data permitted each noise to be defined, examined, and measured independently of each other. The notebooks allowed the data obtained from various visits to a site and from one site to another to be compared.

The instrumentation provided a means to obtain the amplitude of noise at any frequency and to compare the amplitude of noise with the amplitude of any signal present. Thus a means to obtain a useful estimate of signal-to-noise ratio for each individual signal was provided. In addition it was possible to observe and measure changes of noise amplitude and signal-to-noise ratio with time. One difficulty is encountered with measuring the amplitude of the example of impulsive noise such as shown in Figure 3. The bandwidth of impulsive noise is much wider than the IF bandwidth of the spectrum analyzer. Thus, the amplitude of impulsive noise varies significantly with bandwidth. Hodge examined this problem at a number of sites and empirically derived a useful band-width-scaling rule.[2] A plot to convert the amplitude of impulsive noise from one bandwidth to another bandwidth was developed by Hodge, and it is provided in References 1 and 2.

RESULTS

The results provided in this section were accumulated over a period of more than two decades. They were obtained from many visits to both large-scale and small-scale receiving sites located throughout the world. In all cases multiple visits were made to each site at different times of the year, and noise-measurement and noise-mitigation procedures were conducted at some sites several times each year. In addition, numerous auxiliary measurements of man-made noise were made at many other locations including amateur radio stations, commercial radio sites, electric utility sites, and research sites. The results of the auxiliary measurements are not provided in this document, but the results from these additional measurements were consistent with those reported in this paper.

A general overall assessment of noise conditions at the thirty-seven HF receiving sites is provided in Table 1. This table is divided into two portions where the left portion provides general information about each site. A number was assigned to each site (see Column 1) for convenience in keeping track of the data from the various site visits. This is followed by a column identifying the general location of each site to illustrate the wide geographic extent of the collection of data. The third column in the left portion of Table 1 provides a crude representation of the power-pole density within line of sight of each site. Five levels are used to rate the density of power-line poles where "5" represents a large number of poles (more than 500) and decreasing numbers represent fewer poles. This number is followed by the letters "OD" representing "overhead distribution lines", and the letters "OT" representing "overhead transmission lines". The letter "B" was used for sites where all distribution lines within line of sight were buried underground

The right portion of Table 1 provides a summary of noise conditions found at each site along with the identification of the primary and secondary sources of noise. The first column of the right portion of the table provides the noise-level information. The noise from external sources was divided into the four levels with "H" representing a high level of noise. "M" a medium level of noise, "L" a low level, and "VL" a very low level including cases of no external noise.

[2]James W. Hodge, Jr., ***A Comparison Between Power-Line Noise Level Field Measurements and Man-Made Radio Noise Prediction Curves in the High Frequency Band***, MS Thesis, Naval Postgraduate School, Monterey, CA, December 1995

Table 1

Site Noise Summary

SITE PARAMETERS				NOISE SUMMARY	
Site No.	**Site Location**	**PL Status**		**Noise Level**	**Noise Source**
1	North Pacific	B		VL	S
2	Polar	B		VL	S
3	Polar	4,OD		H	P,S
4	Europe	4,OD		M	P,S
5	Europe	B		VL	P
6	Europe	4,OD		H	P,S
7	Europe	1,OD		VL	P,S
8	Caribbean	4,OD		H	S
9	North America	B		VL	P,S
10	North Asia	4,OD		H	P,S
11	North Asia	4,OD		H	P,S
12	North Asia	4,OD		H	P,S
13	Europe	3,OD		M	P,S
14	North Asia	5,OD		H	P,S
15	North Atlantic	3,OD		M	P,S
16	Pacific	4,OD		H	P,S
17	Pacific	4,OD		H	P,S
18	Pacific	4,OD		H	P,S
19	North America	5,OD,OT		H	P,S
20	North America	5,OD		H	P,S
21	North America	4,OD		VL	Ø
22	North America	B		VL	Ø
23	North America	1,OD		L	P
24	Asia	3,OD		H	P,S
25	North America	5,OD		H	P,S
26	North America	5,OD		H	P,S
27	North America	4,OD		M	P,S
28	Europe	5,OD		H	P,S
29	Caribbean	5,OD		H	P,S
30	North America	3,OD		H	T,P
31	South Asia	B		VL	Ø
32	South Asia	B		VL	Ø
33	South Asia	B		VL	Ø
34	South Asia	B		VL	Ø
35	South Asia	B		VL	Ø
36	North America	5,OD,OT		H	P,S
37	North America	4,OD		H	P,S

Letters are used the second column of the right portion of Table 1 to identify the primary and secondary types of sources of noise appearing at the input terminals of each receiver. The letter "P" represents power-line sources, and the letter "T" represents one major source encountered from an electric-powered rail system. The number "Ø" indicates the complete lack of external sources of man-made noise. The letter "S" also appears in the second of the two columns at the right side of Table 1. This letter represents sites that encountered man-made noise from sources located within the site that significantly exceeded the noise floor of receiving systems. The order of the letters indicates the relative magnitude of the noise. In most cases, the noise from site sources was lower in amplitude than the noise from external sources.

A sumary of the information in Table 1 follows:

High-Noise Sites: Twenty sites had high levels of noise from external sources, and eighteen of these sites had a power-line pole-density rating of four or five. Two sites had a power-line pole-density rating of three. None had a lower rating.

Medium-Noise Sites: Four sites with a medium-noise rating all had distribution-line densities of three or four.

Low-Noise Site: The one site with a low-noise rating had only a single distribution line within line of sight. That site was located in a region of high rainfall, a condition that minimizes the activity of most sources of noise on distribution lines.

Very-Low-Noise Sites: Twelve sites fell into the very-low-noise category. Ten of these sites were surrounded exclusively by underground distribution lines. Two sites had overhead distribution lines within line of sight. Of these two, Site 7 had one overhead distribution line that was constructed to noise-free standards, and Site 21 had a power-line density rating of four. Site 21 was a special site where all sources of noise on all overhead lines within line of sight had been eliminated in accordance with the noise-mitigation procedures provided in Reference 1. These lines remained completely noise free for the 12 years of operation of that site.

A direct relationship between man-made noise levels from external-site sources and the density of overhead distribution lines is clearly established from the data. All sites surrounded by overhead distribution lines (except one special case) had high or medium noise levels, and all sites without overhead distribution lines had low noise levels. Insufficient data was obtained to understand the impact of overhead high-voltage transmission power lines on man-made noise at the sites since by design only two sites were located within line of sight of such lines.

Man-made noise from site-related sources was found at twenty-seven of the thirty-seven sites. This was considered a separate problem that should be completely under the control of site personnel, and it is a direct indicator of poor site engineering and/or maintenance.

Sites in the "S" category do not fit into the ITU noise categories discussed later since these categories apply only to external noise sources. For these reasons site-related sources of man-made radio noise are mentioned but are excluded from the primary analysis. The sites with such sources are listed to better understand the extent of this additional but slightly less pervasive problem. Of interest is that sites with the lowest level of internal noise were older sites not yet updated with modern signal distribution and modern digital electronic devices. The older sites did not have excessive noise leakage from internal sources such as: poorly installed digital and RF cables, Uninterruptible Power Supplies, variable-speed motor controllers (often used in air-handling systems), poorly designed switching power supplies, and other modern power-control devices based on switching processes. The measurement teams concluded that a serious internal-noise problem is lurking just below the external-source problem at most of the sites examined, and internal sources will be recognized as a major problem adversely affecting signal reception as the external sources are eliminated.

COMPARISON WITH ITU NOISE MODEL

The model for man-made noise provided by the International Telecommunications Union (ITU)[3] is used for a wide variety of purposes. For example, the ITU model is used in most HF propagation prediction programs, in many communication performance models, and for site planning tasks. The basis for the ITU model was derived several decades ago from extensive measurements of man-made noise levels at a number of locations around the world. These measurements were made from a specific short monopole antenna, and the results are provided in terms of field strength impinging on the monopole.

The data presented in this paper was obtained from the actual antennas used at each site where the antennas varied from dipoles, various versions of monopoles, to large directional arrays. Also, the data was based on noise power measured at the input terminals of 50-Ohm receiving systems. It is not feasible to accurately convert the noise-power data into comparable field-strength data primarily because of major differences between the radiation pattern of the various antennas at each receiving site and that of the ITU monopole. Nevertheless, two simple but pertinent comparisons can be made.

First, the ITU model uses four categories to describe results obtained at the noise-measurement sites that are Business, Residential, Rural, and Quiet Rural. The thirty-seven receiving sites were sorted into these categories as shown in Table 2. The sorting process required some judgement since some sites had residential or business areas remote from a site but still within line of sight. In order to be placed into a residential or business category, a site had to be located adjacent to or reasonably close to a site (within one km). Significant noise sources could not be attributed to the residential or business activities themselves, but hardware items on overhead power lines were found to be major sources of noise. Since no distinction between sources of noise (and the mechanisms generating noise) on overhead power lines around business, residential or rural areas was found, the overhead-line-density ratings were considered the dominant feature rather than residential, business, or rural activities.

In addition, it was difficult to allocate sites to the Rural or Quiet-Rural categories. Sites in these two categories were combined into a single Rural/Quite Rural (R/QR) category. Several such sites had electric utility distribution lines within line of sight that served farming activities as well as the provision of electric power to the sites. In Table 2 the noise at each site is shown using the noise-amplitude designations of Table 1

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[3]CCIR, ***Man-made radio noise***, Report 258-5, International Radio Consultative Committee, International Telecommunications Union, Geneva, Switzerland, 1990

Table 2

Sites by ITU Classification

Site No.	Estimated ITU Classification		
	Business	Resident	R/QR
1			VL
2			VL
3			H
4			M
5	VL		
6			H
7			VL
8			H
9		VL	
10			H
11			H
12			H
13			
14		H	
15			
16			H
17			H
18			H
19			H
20		H	
21		VL	
22	VL		
23			L
24			H
25		H	
26			H
27			
28			H
29			H
30		H	
31			VL
32			VL
33			VL
34			VL
35	VL		
36			H
37			H

Sites Placed in the ITU Rural / Quiet-Rural Categories:. A total of twenty-eight of the thirty-seven sites fell into the combined Rural and Quiet-Rural category. Of these sixteen had high noise levels, four had medium noise levels, one had a low level, and seven had very-low noise levels.

All of the sixteen sites with high noise levels had numerous overhead electric-utility distribution lines within line of sight of their antennas. All sources of external noise were traced to overhead distribution lines.

The three sites with medium noise levels had a modest number of overhead lines within line of sight.. All sources of external noise were traced to overhead distribution lines.

The one low-noise site (Site 23) had a single distribution line. It was located in an area of high rainfall, a weather condition that prevents most radio noise sources on overhead power lines from functioning.

Of the seven sites that had very-low noise levels, five were located in areas with no overhead distribution lines. One had a single overhead power line constructed in accordance with noise-free standards, and the other had a single overhead distribution line operating at less than 1200 Volts, a type of line that seldom generates radio noise.

Sites Placed in the ITU Residential Category: Six sites fell into the Residential category. Four of these sites had high noise levels and two had very-low noise levels. The four sites with high noise levels were all surrounded by overhead distribution power lines, and all sources of external noise were traced to overhead distribution lines. The two sites with very-low noise levels were of special interest. One was entirely surrounded by buried distribution lines. The other was a special case (Site 21) which was surrounded by overhead distribution lines, but all noise sources on all power lines within line of sight had been eliminated by mitigation actions taken in strict accordance with the procedures provided in Reference 1.

Sites Placed in the ITU Business Category: Three sites fell into the Business category. All had very-low noise levels. All facilities near these sites were fed from underground power lines, and no overhead lines were within line of sight of the receiving sites. In addition, none of the buildings in the areas around the sites contained radio-noise-radiating devices.

Next, the reduction in noise amplitude in accordance with the 1/f relationship was examined. This rule was generally consistent where all noise sources were located some distance from a site. A consistent exception to the 1/f relationship for such cases was a reduction in noise amplitude at frequencies below 4 MHz. This reduction was attributed to a decrease in the power generated from sources on power lines below about 4 MHz. This was confirmed by additional measurements in the close vicinity of such sources.

The 1/f rule also failed when sources were very close to a site (less than 1 km). An example of this finding is provided in Figure 2. In this example several active sources of power-line noise were located on a distribution line providing power to the site and on poles within a few hundred meters of the site. The elimination of these nearby sources by effective mitigation actions allowed the man-made noise to revert to the 1/f relationship. One further complication with the 1/f relationship was noted. Sharp nulls and peaks with frequency were always noted (see Figure 4 for an example). These peaks and nulls caused amplitude variations with frequency of 10 to 30 dB.

CONCLUSIONS

Several conclusions were reached from the data accumulated at the thirty-seven sites. They are:

1. Undesirable levels of man-made radio noise from a combination of external and internal sources were encountered at most of the thirty-seven sites. Noise from external sources was the dominant problem at most of the sites, and it was severe enough to significantly degrade the ability of affected sites to receive all but the strongest of radio signals of interest.

2. The time- and frequency-varying aspects of noise from external sources were traced to the erratic operation of individual sources on overhead power lines. Stable noise levels were seldom encountered.

3. A very close relationship was found between man-made radio noise at HF receiving sites and the presence or absence of overhead distribution lines located within line of sight of the uppermost part of the receiving antennas at each site. Only one exception to this finding was noted. In this exception, all noise sources on all overhead lines within line of sight had been eliminated by effective mitigation actions. Sites with no overhead power lines within line of sight were all free from sources of external noise.

2. The ITU categories for man-made noise at HF sites (Business, Residential, Rural, and Quiet Rural) are widely used in communication performance models, for site selection, and for planning purposes. The sites were grouped into these categories, and the noise activity from only external sources was examined to ascertain how well the sites fit each category. Our results show the ITU categories did not provide useful guidelines for noise levels and noise conditions at these receiving sites, and attempts to use the ITU guidelines produced highly misleading results. While the 1/f relationship of noise amplitude with frequency was crudely followed at several of the sites, significant exceptions to this relationship were found (i.e., see Figure 2). Also, significant fine-scale nulls and peaks in the spectral structure of noise were found at most sites that are not taken into account by the 1/f relationship unless data is averaged over time, frequency, or multiple sites.

3. The relatively old data used to define the ITU man-made-noise model urgently needs to be updated.

4. The results suggest that a new model for man-made noise based on the number of power poles within line of sight of the uppermost part of a receiving site's antenna would provide more realistic results than the ITU model. Should all sources of noise from power lines be eliminated by effective mitigation actions at some future time, this suggested model will also be ineffective.

5. Many of the receiving sites also experienced significant levels of man-made noise at receiver input terminals from sources within the sites. This is a separate problem that will become the primary problem as external sources are eliminated. Internal noise was traced to a variety of sources. Examples of internal sources are power-control devices (including, poorly-designed switching power supplies, variable-speed motor drives, light-dimmer controls, and other similar devices), faulty and improperly installed ballasts for internal and external lights, improperly installed cables carrying digital signals, improperly installed RF cables, leakage into single-shielded coaxial cables used to carry low-level RF signals), new high-efficiency lighting systems, intermodulaton products from current flowing through welded joints in galvanized metal, and intermodulation products generated by overloaded components in RF distribution systems.

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THE MITIGATION OF RADIO NOISE FROM EXTERNAL SOURCES
at
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6TH EDITION

May 2007

by
Wilbur R. Vincent, George F. Munsch,
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ABSTRACT *(maximum 200 words)* *Procedures to locate radio-noise sources, identify source hardware, and mitigate noise problems are provided where the sources are external to a receiving site. In addition, procedures to assess the impact of man-made radio noise on signal reception are included. These procedures were developed over three decades of radio-noise investigations at more than 45 radio-receiving sites.*

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PREFACE

This is the sixth edition of this handbook. Periodic updates are necessary to cope with new sources of radio noise, new source-location and source-identification techniques, and improved procedures for mitigating sources. In past years the dominant noise at receiving sites was from sources on power lines. In more recent time, radio noise from power-conversion devices operated by customers of electric utilities has become a significant source, and a section on such sources is included in this edition.

The title of this edition has been slightly changed to better accommodate new noise-mitigation information and the new sources. In addition, the title limits the content of this handbook to sources external to receiving sites. A companion handbook covering sources of radio noise internal to a receiving facility is in preparation.

Editions 1 and 2 of this document were published and distributed by the Southwest Research Institute of San Antonio, Texas in 1993. These two early editions formalized hand written notes on power-line noise mitigation, and they were provided to US Navy Signal-to-Noise Enhancement Teams to aid in their task of minimizing the adverse impact of power-line noise on the reception of radio signals at US Navy radio-receiving sites. The procedures provided in the handbook proved to be highly effective when the teams were adequately trained and when the procedures were strictly followed. All copies of the first two editions were quickly distributed to interested parties. Since there was an ongoing demand for additional copies, a second printing of Edition 2 was provided by the Naval Postgraduate School, Monterey, CA. Engineering Research Associates of Vienna, Virginia provided a third printing of Edition 2.

The second edition was translated into Japanese to support mitigation programs in Japan, into Spanish for use in Spain and Puerto Rico and into Korean for use in Korea. The first two translations were provided by Engineering Research Associates, and the third translation by the Mission Support Activity (MSA) of USA INSCOM. Argon Engineering of Vienna, Virginia has produced a Japanese translation of the fifth edition for use in Japan.

This edition adds considerable information about radio noise from power-conversion devices, a new source of radio noise that has appeared from the use of modern solid-state switching devices to alter and control electric power supplied to various kinds of loads.

The authors are grateful to the Signal Enhancement Laboratory of the Electrical and Computer Engineering Department of the Naval Postgraduate School for their ongoing interest in keeping this handbook up to date.

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1. INTRODUCTION

Radio noise from sources associated with hardware on distribution power lines was the primary kind of radio noise affecting the signal-reception capability of radio receiving sites for many years. Only a very few remote sites that did not obtain power from overhead distribution lines and did not have distribution lines within line of sight of the uppermost part of antennas were free from the noise problems described in this document.

In recent years radio-noise from power-conversion devices has appeared, and it is now an additional problem at many HF through UHF radio-receiving sites. This edition of the handbook adds information about this relatively new source of radio noise. The handbook has been reorganized to add information about new sources and other new material, but the extensive information about sources associated with electric-power-distribution lines in the earlier editions is retained.

A five-step program is described to eliminate external sources of man-made noise from a receiving site. They are:

Step 1—Understand and define the noise problem at a receiving site.
Step 2—Understand sources and source mechanisms.
Step 3—Locate sources.
Step 4—Identify the hardware which is generating noise.
Step 5—Specify and execute an effective mitigation action for each source.

The presentation in this edition of the handbook follows the above steps. Typical noise problems at a receiving site are described in Section 1. Typical sources, source mechanisms and the temporal and spectral properties of noise from a variety of common sources are described in Section 2. Section 3 presents effective ways to locate sources of noise affecting the reception of signals at a site. Section 4 provides techniques to identify the specific items of hardware which generate noise. Section 5 presents effective and ineffective noise-mitigation actions.

Appendix A provides a convenient summary of techniques to build noise-free electric-power distribution lines. Sections of distribution lines constructed in accordance with these techniques and procedures have remained completely free of sources of radio noise during more than a decade of monitoring.

Appendix B describes a realistic method of calculating the loss of signal-reception capability from sources of man-made radio noise, and this technique is often used at the completion of a site survey. An example of signal-reception loss is provided from man-made radio-noise problems at a major receiving site, primarily noise from sources on power lines. The example employs measured noise data, measured site parameters, and is for a specific site, year, and season.

The power-line material in this handbook is directed at the mitigation of noise sources associated with overhead distribution power lines (the lines providing electric power to customers). Sources on transmission lines (the lines interconnecting power plants, interconnecting transmission-line substations, and providing power to transmission substations) are usually more remote from receiving sites and such lines usually have fewer sources. In addition, the safety requirements associated with the higher voltages of transmission lines (69kV to 1MV) are critical and beyond the scope of this handbook.

The planners, managers, and staff of receiving sites have historically given a low priority to radio-noise problems. This is because effective and practical instrumentation to identify and document radio-noise problems in meaningful terms is rarely available at a site. In addition a means to determine its impact on the reception of radio signals at a site is seldom available. Radio-noise problems are often perverse, and they take special techniques and considerable practical field experience to resolve. This handbook fills some of the gaps in the process of resolving radio-noise problems.

Shortcuts to the procedures provided in this handbook are not advised since they almost always lead to incorrect results, excessive expenditures of manpower and money, and ineffective noise-elimination actions. Detailed knowledge of the procedures in this handbook and the strict adherence to the procedures will result in the elimination of noise sources. The reader is cautioned that extensive field experience is a necessary aspect of the successful and complete mitigation of the noise sources described in this handbook. There is no quick and easy way to successfully undertake the tasks of radio-noise mitigation.

Many sites have additional radio-noise problems from sources internal to a site. This handbook does not cover this additional aspect of sources of noise affecting the reception of radio signals. A companion document that deals with this important problem is in draft form.

2. Step 1—THE SITE NOISE PROBLEM

2.1 Background and General Approach

Considerable background information is required to understand whether a receiving site has experienced harmful interference from external sources of noise. A few sites encounter no noise from external sources, thus they have no need for this handbook. Other sites encounter severe levels of radio noise from external sources along with the associated loss of signal-detection capability. Generalized comments about radio noise and radio interference are not sufficient to determine if harmful levels of noise are present, to determine is noise is from internal or external sources, to locate sources, and to undertake effective noise-mitigation actions. This section of the handbook is intended to familiarize the reader with some of the background information needed to investigate and solve site noise problems.

It is useful to first understand the general signal population in the HF band and to relate signals of primary interest to the general signal population. Figure 1 shows an example of the signal levels received in the 8- to 18-MHz portion of the HF band. The signal amplitudes were obtained at 1600 local time, a time of day when the general signal population and signal levels were lowest. Only a few low-level signals were present above and below the frequency range shown due to propagation conditions. The groups of highest-level signals in Figure 1 are signals from transmitters in the International Broadcast Service. They represent signals in the 31-, 25-, 22-, 19-, and 16-meter bands internationally allocated to that service. At nighttime when ionospheric absorption is low, signals in these groups will be 30- to 50-dB higher in amplitude than shown in this figure.

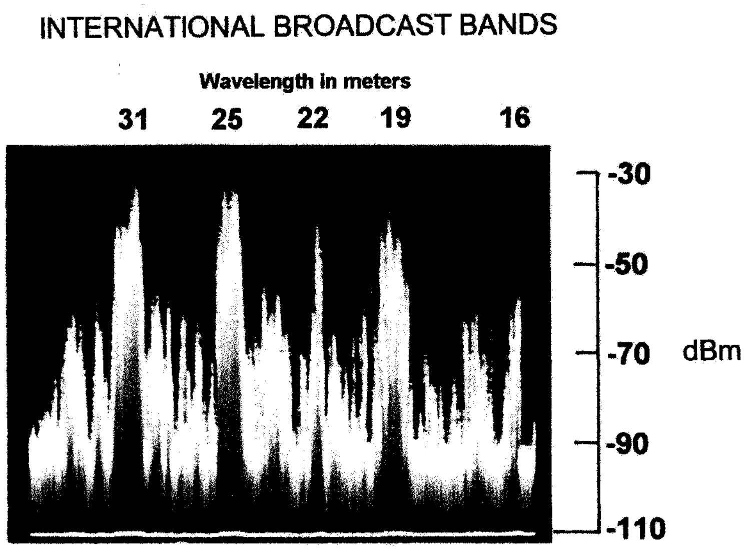


Figure 1 Example of Daytime Signal Levels in the HF Band

Most signals of primary interest will be located at frequencies between, above, and below signals in the International Broadcast Bands shown in Figure 1. The level of most signals of concern will be much lower in amplitude than those in the International Broadcast service, and they will generally range from a peak of about -80 dBm down to the minimum detectable level of about -130 dBm for a receiver with a 3-kHz bandwidth. Radio receivers and noise-measurement instrumentation must be capable of coping with high-level signals in the International Broadcast Bands while also receiving signals and noise at the minimum signal-detection level of about -130 dBm.

All broadband components of the RF path from the antenna to a receiver must be capable of coping with the total signal power delivered by the antenna without becoming saturated. In addition, the receivers and noise-measurement instrumentation at a site must also be able to cope with the total signal and noise power delivered to them. To obtain general information about the nature of signals in the band, the total signal and noise power delivered by an omni-directional antenna to a 50-Ohm load was measured at a number of HF receiving sites over one- to four-day periods with a broadband rms. voltmeter. A bandpass filter of 2- to 30-MHz was used between the antenna and the voltmeter to prevent signals lower and higher in frequency from contaminating the results. This measurement was completed at several sites to understand the maximum power levels presented to the input terminals of site receivers and at the input terminals of the noise instrumentation.

Figure 2 shows an example of the total power delivered from an omidirectional antenna to a 50-Ohm load over a 4-day period. This example was obtained from a European location, but almost identical examples were obtained from all other locations. As shown, daytime power levels are reduced by signal absorption in the propagation path. Nighttime absorption levels are lower, resulting in higher signal levels and higher total power delivered by an antenna.

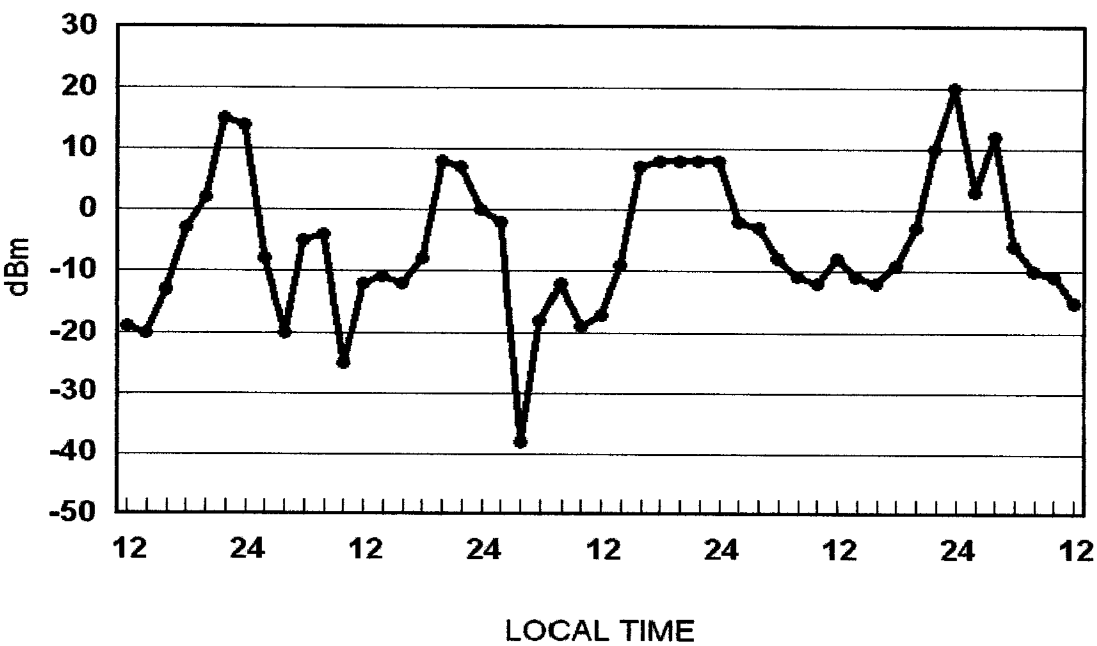


Figure 2 Total Signal Power Delivered from an Antenna

The noise floor of a typical HF receiver is about –130 dBm for a 3-kHz bandwidth. This indicates that the broadband dynamic range of components in the RF path from the antenna to a receiver, and in the front-end portion of a receiver or noise instrumentation, must be about 100 dB for the daytime measurement of noise at a receiving site. A broadband dynamic range of about 140 dB is required to ensure that nighttime noise data will not be contaminated by inter-modulation products or inter-modulation noise generated by components in the RF path between the antenna and the receiver. Alternatively, filters can be used to reduce the level of the broadcast band signals. Daytime noise measurements can usually be made by the careful use of conventional instrumentation. While some care must be made to ensure that instrumentation has sufficient dynamic range to handle the daytime signal power, much greater care must be taken to cope with the increased nighttime signal power.

Yet another problem exists for the measurement of man-made radio noise in the HF band. Such noise is often highly impulsive. The spectral components of impulses are generally much wider than the measurement bandwidth of a conventional HF receiver or the bandwidth of noise-measurement instrumentation. Since little information about the impact of measurement bandwidth on noise amplitude was available, Hodge[1] investigated the problem and developed a plot for bandwidth conversion.

Figure 3 shows how the amplitude of power-line noise changes with instrumentation bandwidth. A similar plot of the amplitude of time-stable Gaussian noise as bandwidth is changed is added to the figure for reference purposes. The amplitude of a discrete-frequency signal does not change with bandwidth.

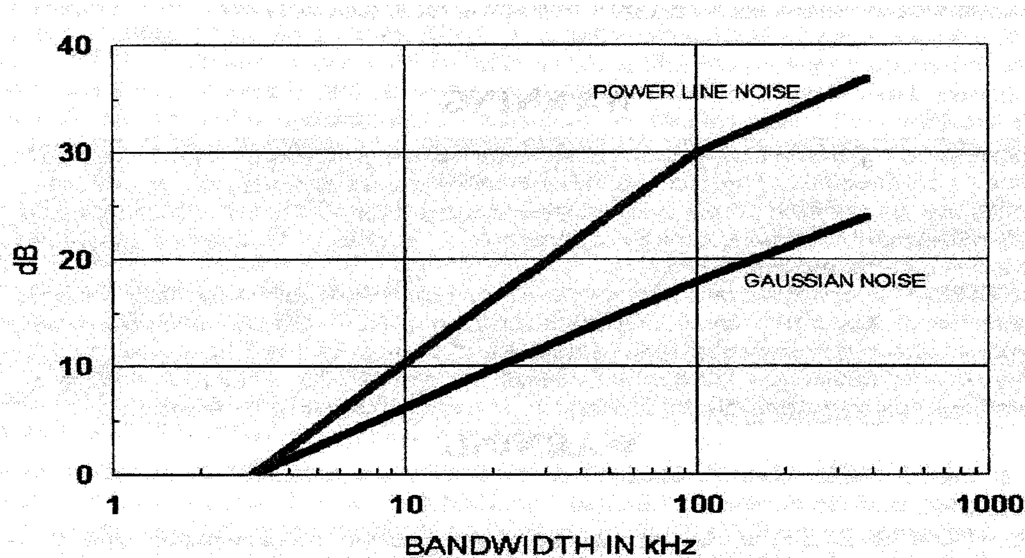


Figure 3 Bandwidth Scaling Curve for Power-Line Noise

[1] James W. Hodge, *A Comparison between Power-line Noise Level Field Measurements and Man-Made Radio Noise Prediction Curves in the High-Frequency Radio Band*, MS Thesis, Naval Postgraduate School, Monterey, CA., December 1995

Preliminary data about the amplitude of noise from a few power-conversion devices has been collected as receiver bandwidth was changed. Figure 4 shows plots of data from two types of motor controllers. Again a line representing variation in the amplitude of time-stable Gaussian noise with bandwidth is added to the plot for reference purposes.

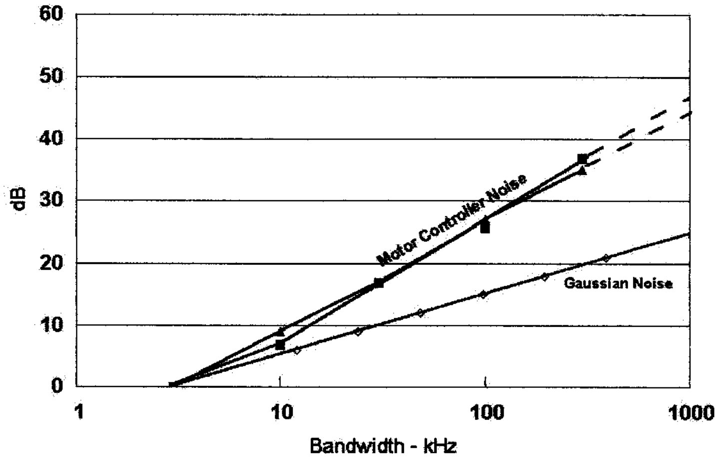


Figure 4 Preliminary Bandwidth Scaling Curve for Power-Conversion Noise

Because of measurement bandwidth implications on noise amplitude, the actual measurement bandwidth for each example of data shown in this document is provided. In addition, all measurements were made with a Gaussian-shaped bandwidth to minimize pulse-distortion effects. Considerable care was taken to ensure that all measurements were made under linear conditions to avoid contamination from intermodulation products and broadband intermodulation noise.

Occasionally one will encounter a nonlinear device during noise measurements at a receiving site. The term "Intermodulation Products" is often used to describe the resulting spectral components generated by a nonlinear device. However, "Intermodulation Products" is commonly used to define the result of mixing multiple discrete-frequency signals together in a nonlinear component where the original and the additional spectral components generated are all discrete in frequency. Intermodulation products are highly useful for many laboratory measurements where clean signals are generated by signal generators, but it does not describe the intermodulation results found at a receiving site. A receiving site encounters many signals that are wide in spectral content (examples are FM, SSB, spread spectrum, repetitive impulses, random impulses, etc.). The intermodulation products of such signals are spectrally wide and change in amplitude and occurrence as signals fade, come and go. The term "Intermodulation Noise" is used in this document to distinguish the additional wideband spectral components generated in a nonlinear device while the term "Intermodulation Components" is used in its conventional sense.

2.2 Site Instrumentation

Instrumentation is required inside the receiving site to verify that radio noise and interference from power lines is present at the input terminals of receivers and to document the technical properties of such interference. Special importance is given to this instrumentation since it must present the investigator with sufficient information to determine the adverse impact of noise on signal reception, differentiate power-line noise from power-converter noise, and define noise from other sources. The instrumentation must also be able to cope with, and define, the highly erratic and time-changing operation of individual sources as well as multiple sources.

The site instrumentation must be capable of accomplishing a variety of measurement tasks. Examples of these tasks are:

- Identify and measure the ambient noise floor presented to the input terminals of a receiver in the absence of man-made radio noise.
- Identify and sort power-line noise and power-conversion noise from a variety of other kinds of noise.
- Identify and describe multiple cases and types of noise.
- Identify the primary spectral and temporal properties of each source of noise.
- Identify brief bursts of noise and sort them from other noise bursts, signal bursts, transients, and other ambient signals and noise.
- Cope with and define highly erratic time-varying noise.
- Identify, sort, and distinguish between cases of non-stationary noise and non-stationary signals.
- Document the technical characteristics of each case of harmful radio noise.
- If possible, provide directional information toward each source of noise to external source-location teams.
- Coordinate the observed temporal structure of each case of power-line noise with that observed by external source-location teams in real time.

This handbook does not include instrumentation to obtain long-term statistical measures of man-made radio noise. That is a separate matter that is beyond the scope and objectives of this handbook. The information and the instrumentation described in this handbook are limited to the objectives stated in Section 1.

Figure 5 shows a block diagram of the primary site-located instrumentation used to obtain the data presented in this document.

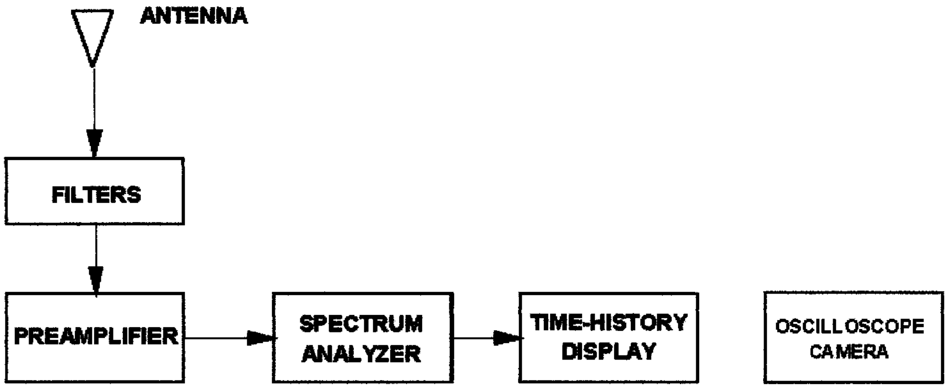


Figure 5 Block Diagram of Site Instrumentation

The antenna should be the one normally used for signal reception at a site. Furthermore, the instrumentation should be connected to the antenna at a location near the receiver. This will allow the instrumentation to examine the same radio-noise conditions which the receiver encounters.

Banks of band-pass filters are used to avoid the high signal strengths found in the International Broadcast Bands. Unfortunately, it is not possible to design conventional discrete-component filters to completely avoid all of the high-level signals in the HF band. The filters were often supplemented with a narrow-band preselector of the kind popular in the early days of radio. Between the filters and a preselector it is possible to obtain sufficient information about low-level signals and noise to achieve the program objectives.

High dynamic range preamplifiers were used to set the noise floor of the instrumentation about equal to that of a standard HF/VHF/UHF receiver.

The spectrum analyzer is the critical part of the instrumentation. A scanning analyzer is preferred, but many new digital scanning analyzers are unsuitable for two reasons. First, the dead time between scans is far too large, resulting in excessive missed information along with their inability to define cases of erratic and intermittent noise. Second, it is impossible to alter their adjustments fast enough to define many cases of intermittent and short-term noise. For these reasons hand-selected units of the older HP-141 type Spectrum Analyzers were used to collect the data shown in this document. The dead time between scans for the older analyzer is minimal, and its controls can be rapidly adjusted to cope with changing conditions. Newer models of scanning spectrum analyzers are desired to replace the older model used for noise measurements, but suitable models were not available at the time this document was prepared. However, presently available newer models were preferred for laboratory measurements of time-stable signals and noise.

An ELF Engineering Model 7200B 3-Axis Display was interfaced to the HP 141 Spectrum Analyzer to provide a real-time time-history display of the temporal and spectral properties of signals and noise in any portion of the HF, VHF or UHF bands. The time-history presentation of the display provides its operator with comprehensive information about the time-changing signals and noise as well as those of more stable sources of signals and noise. The time-history view is often optimized by adjusting the spectrum analyzer scan-time control to a value considerably longer than the repetitive period of power-line noise (8.3 or 16.6 ms for a 60-Hz line and 10 or 20 ms for a 50-Hz line). A scan time of 100 or 200 ms allows several bursts of wide-band impulsive noise to occur during each scan. This provides an excellent view of the coarse-scale temporal and spectral structure. The interaction of repetitive bursts of power-line or power-converter noise with the slower scan time results in slanting lines across the time-history view. This provides an effective means to quickly determine the primary properties of each case of noise and to distinguish power-line noise from other types of signals and noise.

In past years the time-history views were photographed with oscilloscope cameras using Polaroid film. This camera has been replaced with a digital oscilloscope camera, and the resulting digital files are stored on a laptop computer.

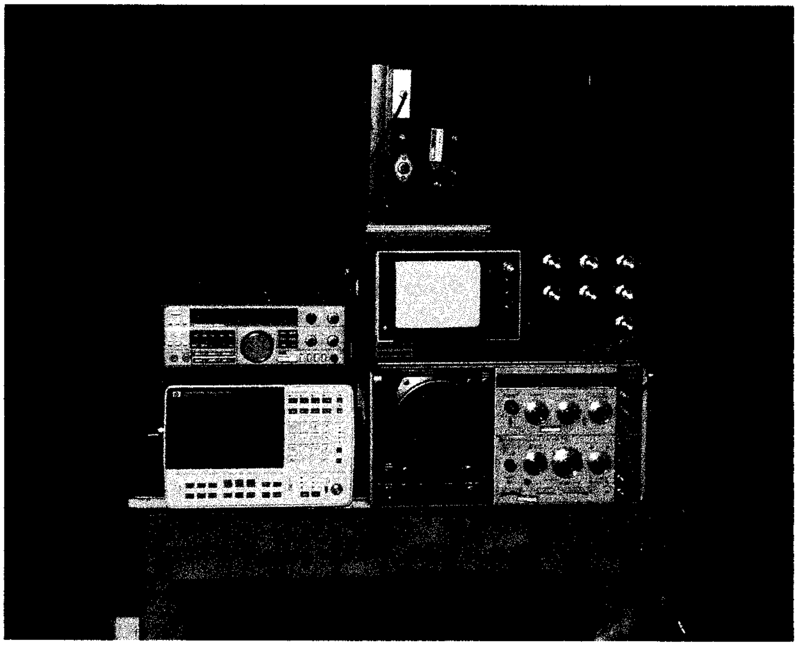


Figure 6 Photograph of Typical Site Instrumentation

Some sites may not have suitable real-time instrumentation for source-location, source-identification, and source-mitigation tasks. For such sites, the spectrum analyzer can be replaced with the Radar Engineers, Inc. Model 240 or 242 RFI Locators described in Section 3.

2.3 Coarse-Scale Properties of Power-Line Noise

This section of the handbook describes the primary properties of radio noise from sources on power poles. Several examples of the coarse-scale temporal and spectral properties of power-line noise obtained at receiving sites are provided to illustrate its impact on signal reception. The fine-scale temporal properties of such noise are highly useful in identifying sources, and several examples are provided in the following section.

Figure 7 shows an example of the coarse-scale temporal and spectral structure of noise from a source on a power line. This example of severe noise from sources on a distribution line was obtained at a large receiving site and from an operational antenna at that site. The distribution line poles containing the sources were more than 1 km from the site.

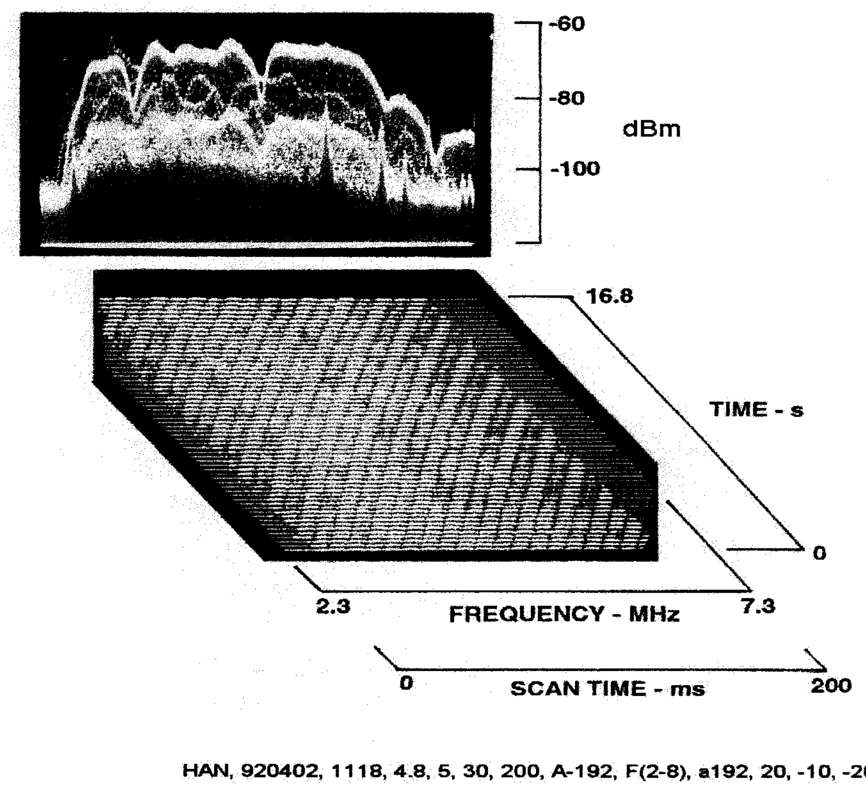


Figure 7 Coarse-Scale Properties of Power-Line Noise, Example 1

Two views of the same data are provided in Figure 7. The top view shows noise amplitude vs. frequency. Noise amplitude can be obtained from the scale on the right end of the view. This scale provides the peak noise power within the bandwidth of the measurement system that is delivered to a 50-Ohm receiver. Multiple sources of noise (at least 4) with differing spectral shapes are shown in this view. The frequency scale shown below the bottom view also applies to the top view.

Deep nulls and high peaks in amplitude across the 5-MHz frequency band are shown in Figure 7. These peaks and nulls are caused by the non-frequency-flat characteristics of the source and spectral distortion from items in the path between the source and a receiver. The peaks and nulls make it impossible to define noise amplitude by a single number except at a specific frequency. The rather sharp fall in amplitude at the lower end of the frequency scale was caused by the use of a band-pass filter (band pass of 2 to 8 MHz) to limit the total signal and noise power fed to the instrumentation. The reduction in amplitude at the upper end of the frequency scale is associated with the spectral content and shape of the noise.

A close inspection of the upper view shows a few discrete-frequency signals near the upper end of the frequency scale, but the noise level exceeded all signal levels. Signal reception was not feasible with the presence of this noise.

The lower view provides a time-history picture of the activity of the sources. In this case the sources were active for the full 16.8 seconds duration of the example. Later examples will show the more typical erratic operation of noise sources. The slanting lines across the time-history view are a result of the bursts of broad-band noise occurring at the voltage peaks on a nearby distribution line interacting with the slower scan time of the spectrum analyzer used to obtain the example. The noise bursts are separated by 8.33 ms while the scan time is 200 ms.

This example shows severe radio noise originating from sources on an electric-power distribution line where the nearest source was more than one km from the antennas at the site. The example illustrates the adverse impact radio noise can have on signal reception. The maximum amplitude of typical signals of interest to the site is about –80 dBm, a further indication of the adverse impact of the noise.

Since the noise shown in Figure 7 is impulsive, its amplitude is limited by the measurement-system bandwidth (30 kHz for this example). The noise amplitude can be scaled to any desired receiver bandwidth using the curve in Figure 3. The amplitude of discrete-frequency signals can be obtained from the amplitude scale.

A small line of information is provided at the bottom of this and all subsequent examples. The parameters in this line provide information about the measurement as well as key instrumentation parameters. Each item listed in the line is separated by a comma, and they are:

Site identification, date in yymmdd format, local time, center frequency in MHz, frequency span in MHz, IF bandwidth in kHz, scan time in ms, antenna identification, filter identification, preamplifier gain in dB, IF reference level, and RF attenuation.

Figure 8 shows a case where the source of power-line noise is erratic in operation as shown in the time-history view. In this case the source was only about 100 meters from the receiver site, allowing noise to be received up into the VHF band.

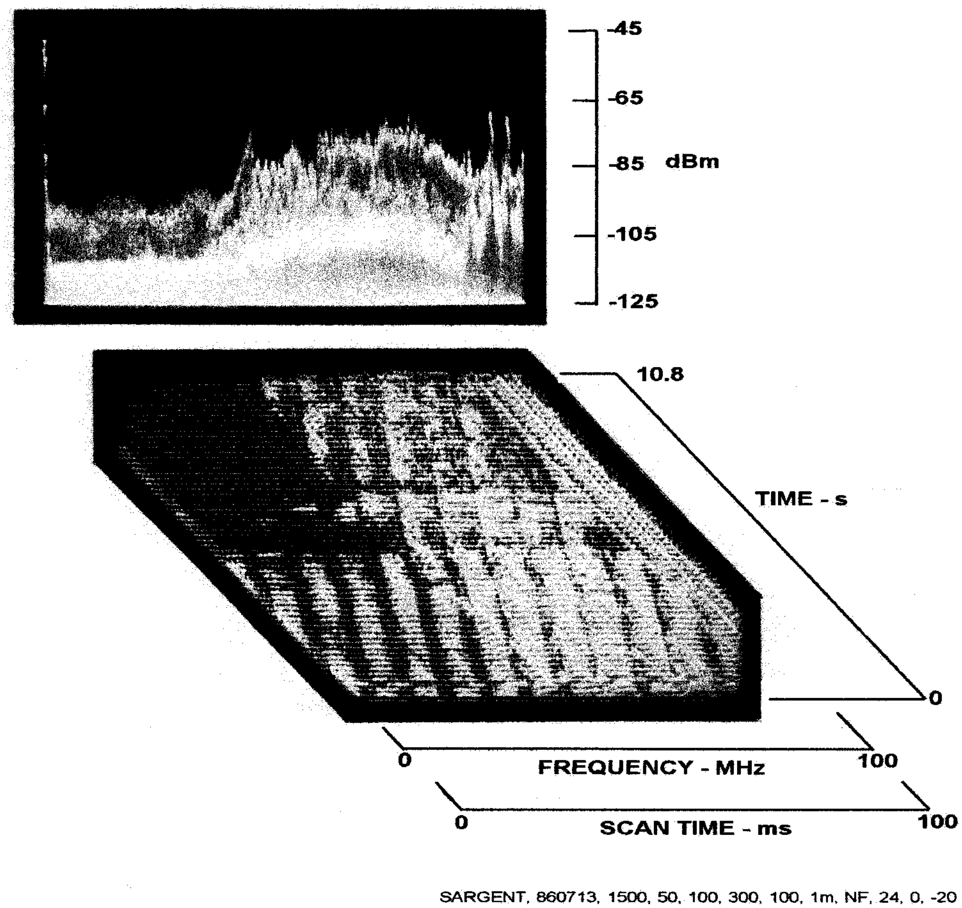


Figure 8 Coarse-Scale Properties of Power-Line Noise, Example 2

One noise source was active for the entire time of the observation of Figure 8. The amplitude of this source was higher at the VHF frequencies of 40 to 100 MHz than for the 2- to 30-MHz HF band. A second source became active about ½ way down the time axis of the time-history view. The second source added additional radio noise to the HF band and added very high noise into the VHF band up to and beyond 100 MHz.

The slanting lines are further apart than those in Figure 7 because of the use of a faster scan time of 100 ms compared with 200 ms for the prior example. Since the bursts of noise from the two sources overlap in the time-history view, the two sources are on the same phase of a three-phase overhead distribution line.

Figure 9 shows another example of the erratic impact of power-line noise on the reception of signals. In this case the source was located more than a km from the receiving site. The time-history view shows the erratic operation of the source. The upper view shows that each burst of noise has the same spectral structure, indicating that each burst of noise is from the same erratically-operating source. The peaks and nulls in amplitude are well defined.

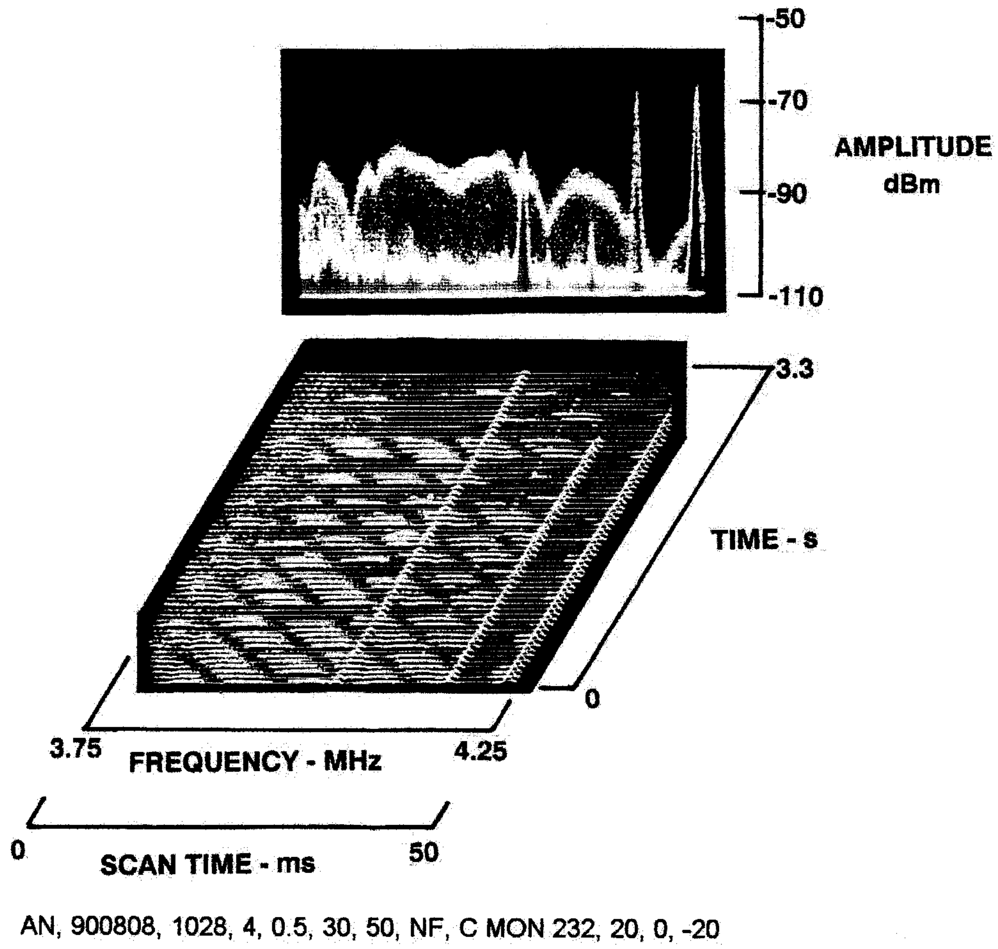
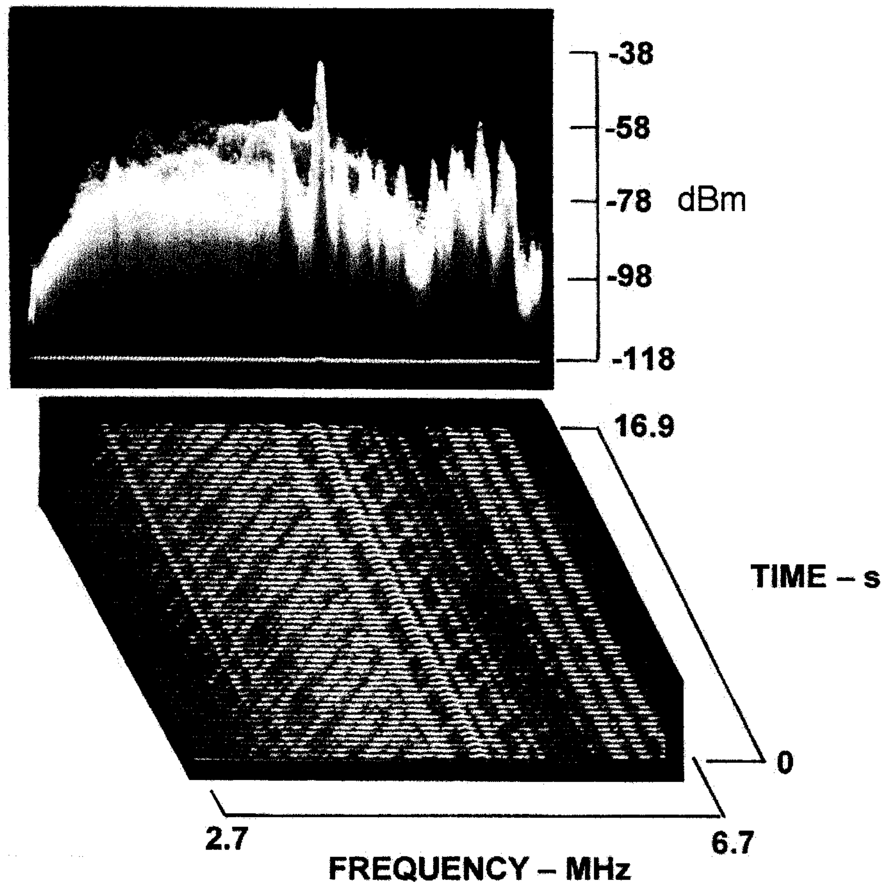


Figure 9 Coarse-Scale Properties of Power-Line Noise, Example 3

Two strong signals near the upper end of the frequency scale exceeded the noise and could be received. One signal slightly above 4 MHz exceeded the noise by a slight amount, and it could be received along with noise. Another signal can be seen about ¾ of the way up the frequency scale that is below the noise level and could not be received during the noise bursts, but it could be received in the brief intervals between each noise burst.

Figure 10 shows an example of noise from multiple sources on a distribution line. The lower view shows that sources are on two phases of a 3-phase distribution line. Both sources were more than 2 km from the site. The upper view shows the spectral shape of each source as well as several discrete-frequency signals.



ROT, 000906, 0835, 4.2, 5, 30, 200, LBM 120, PS-3, BPF 2-6, 11, 0, -30

Figure 10 Coarse-Scale Properties of Power-Line Noise, Example 4

The non-flat spectral content of each sources of power-line noise is shown in the amplitude vs.-frequency view. The signal-to-noise ratio of each individual signal can be determined from the data. Signals without sufficient amplitude margin over the noise cannot be received.

One final example of the gross spectral content of noise from a source on a power line is provided in Figure 11. In this case multiple sources of noise were present from three bell insulators on a pole located about 100 meters from the receiving site's antenna. This line provided electric power to this site and to another site several km further away.

Severe noise was noted throughout the entire HF and VHF bands and up into the UHF band. The sources were eliminated by replacing the bells with polymer insulators. After replacement the noise floor dropped significantly across the entire frequency span of the data, and the site was able to resume normal signal-reception tasks in all bands. Only a few cases of low-level noise remained from more distant sources. The nearby sources had to be eliminated before the lower-level and more distant sources could be detected and be dealt with.

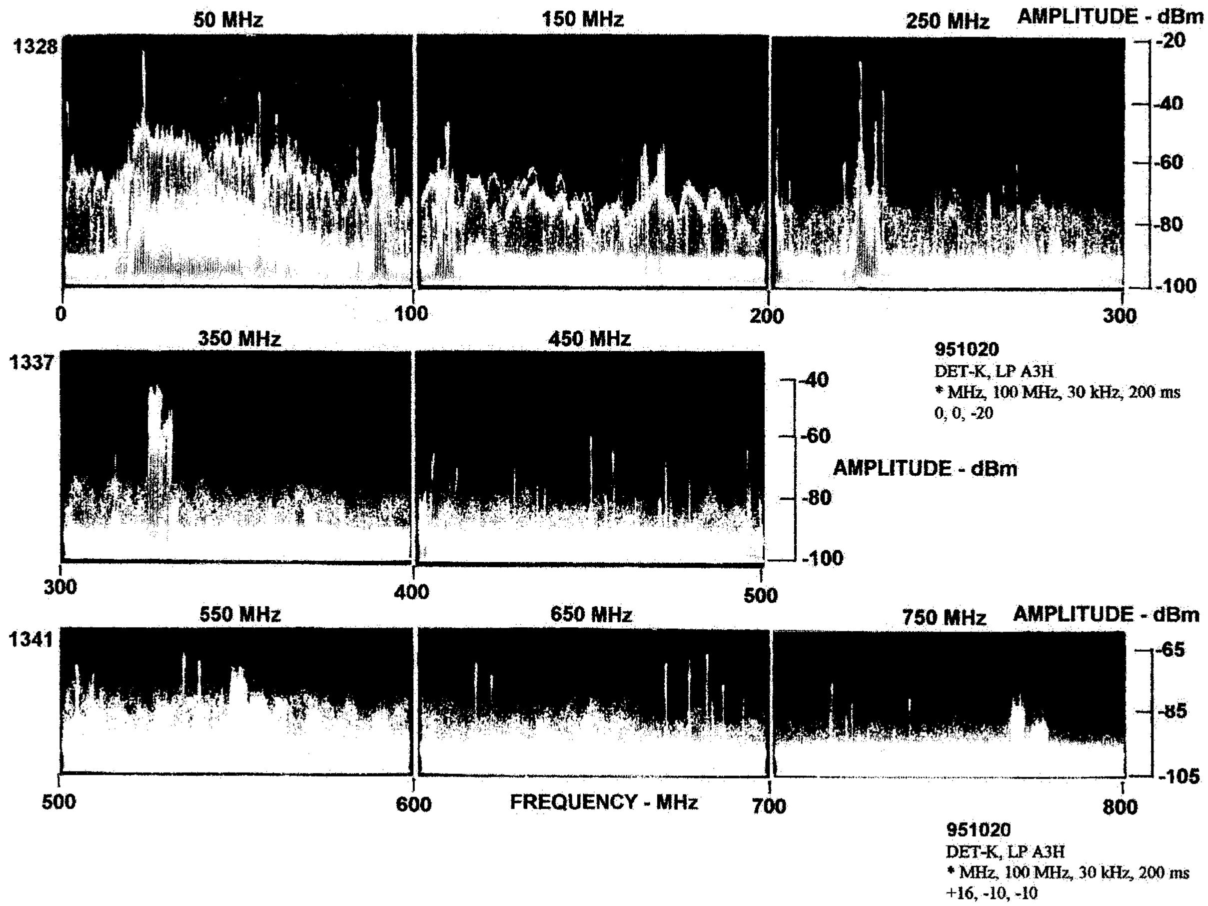


Figure 11 Noise at a HF/VHF/UHF Site

2.4 Fine-Scale Properties of Power-Line Noise

Knowledge of the fine-scale temporal structure of power-line noise provides considerable information about each source of noise. Such information when obtained at the site is essential for the successful completion of external source-location and source-hardware identification efforts.

Two common types of noise will be encountered along with several less common types. These types are closely related to the source mechanisms. The first is sometimes referred to as "gap noise" and its source is the very small breakdown of an insulating oxide layer between two metal components. The second common type is from the breakdown of air between two closely-spaced conducting objects. The first type is called *micro sparking* in this document. The second is called *sparking*.

Figure 11 shows an example of the fine-scale presentation of the micro sparking. This source was traced to the breakdown of the oxide layer between the two metal parts of the clevis and pin joining two parts of a dual bell insulator.

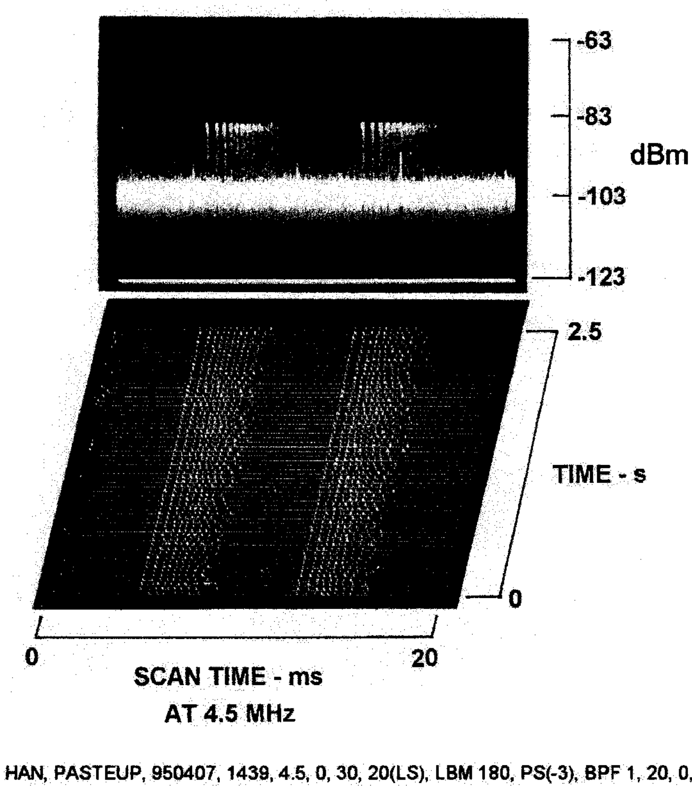
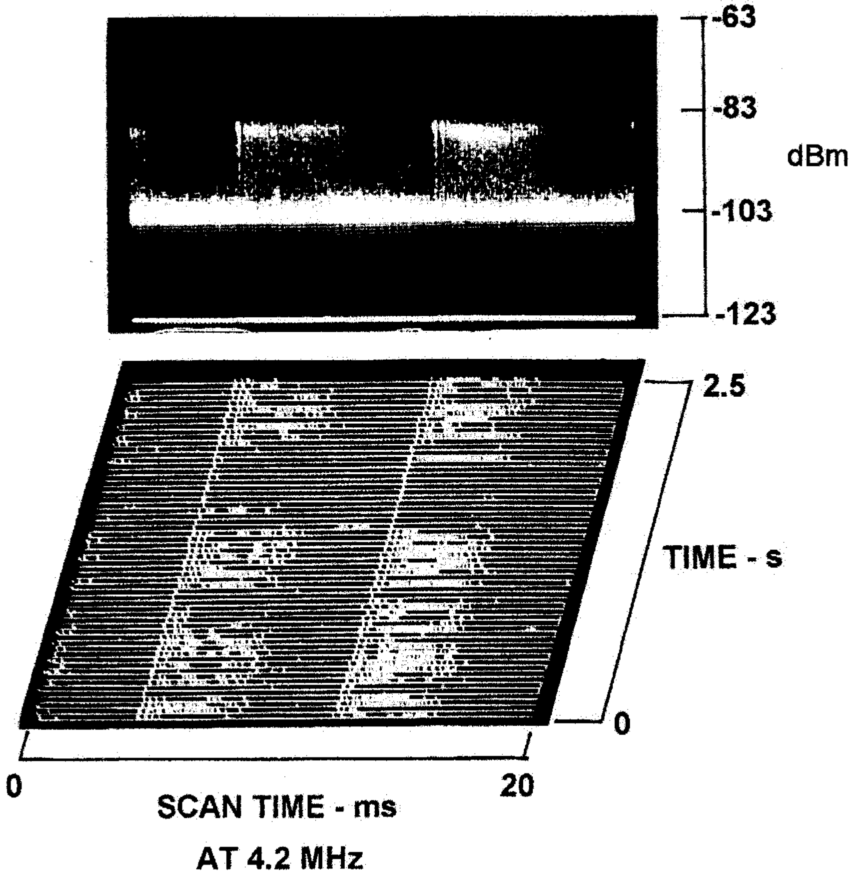


Figure 12 Fine-Scale Temporal Structure, Example 1

The example in Figure 12 was obtained with the scan process of the spectrum analyzer synchronized to the power-line frequency. The scan time of 20 ms resulted in bursts of noise in the view where the bursts are separated by 8.33 ms. The timing of the first impulse of each group is very stable, and it occurs when the power-line voltage reaches the breakdown point of a thin insulating oxide layer. Successive impulses occur in accordance with the model of the breakdown process provided in Section 3. The timing of subsequent breakdowns is less stable, and the creation of the impulses stops when the power-line voltage falls below the breakdown point of the thin oxide layer. This process results in a succession of bursts of noise where the bursts are synchronized to the power-line frequency. The amplitude of each impulse is almost identical. This and the pulse-spacing pattern result in a distinctive temporal structure that is easy to recognize during noise measurements at a receiving site. The noise creation and radiation mechanism is described more fully in Section 3.

Figure 13 shows a case where the breakdown process is erratic. Such a source can quickly change from continuous operation to intermittent operation and back, or it can remain in a stable state for minutes to tens of minutes.



HAN, PASTEUP, 950407, 1502, 4.2, 0, 30, 20(LS), LBM 180, PS(-3), BPF 1, 20, 0, -20

Figure 13 Fine Scale Temporal Structure, Example 2

Figure 14 shows an example of micro-sparking noise from a bell insulator source where the insulator was moving slightly from wind. The data was obtained with the scan time of the spectrum analyzer synchronized to the power-line frequency. Slight changes in the physical configuration of the oxide-layer breakdown from wind movement can produce large changes in the temporal structure of the noise. A few minutes after this example was obtained, the source became inactive for the remainder of the day.

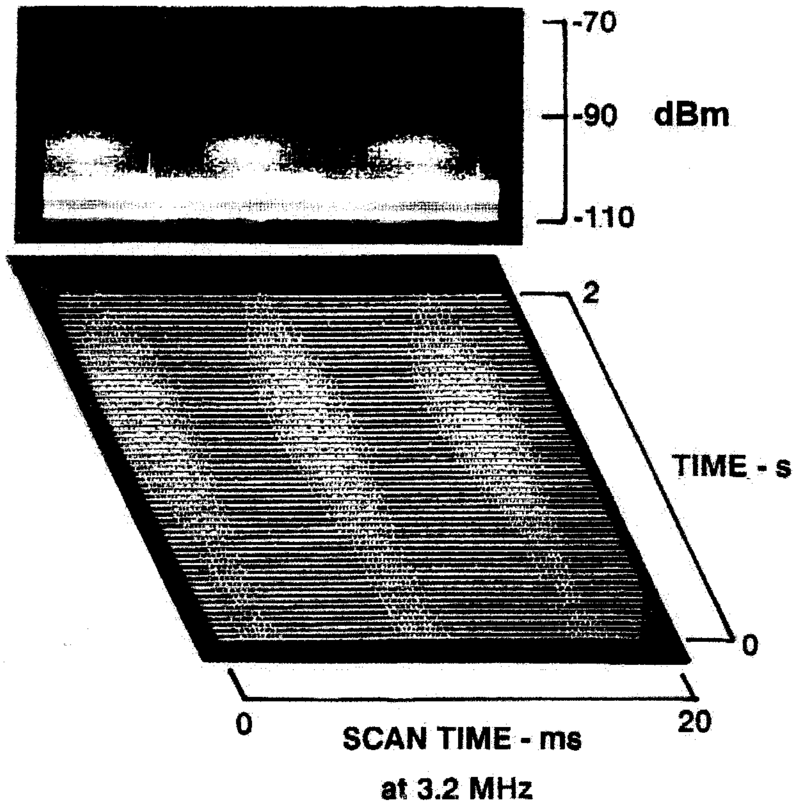
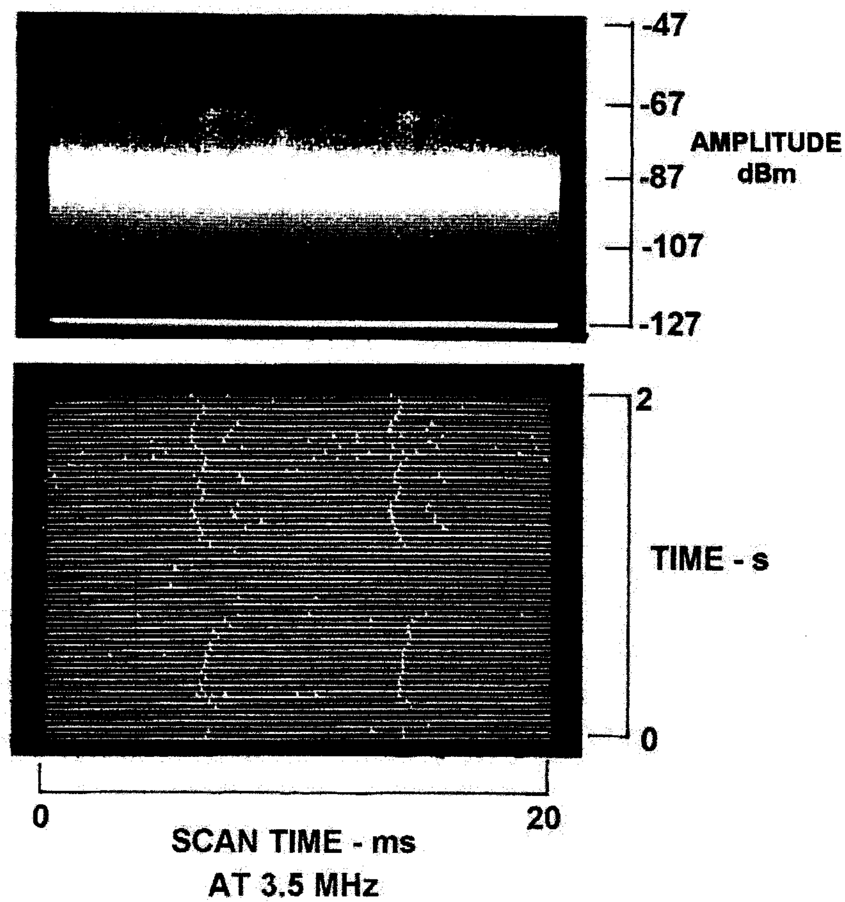


Figure 14 Fine-Scale Temporal Structure, Example 3

The sources of the microsparking noise shown in the previous three figures are frequently hidden behind metal objects, and the spark is so small that it is not visible to the eye. Also it does not produce sufficient energy to result in reliable detection with an infrared sensor. Noise from this kind of source can be reliably detected with a VHF RF probe.

Figure 15 shows an entirely different fine-scale temporal structure. This example of sparking noise was caused by the erratic breakdown of air at the end of an insulated tie wire used to fasten an insulated conductor to a post insulator. The source was several km from the receiving site. The erratic initiation time of the initial arc is shown in the time-history view along with a more erratic second arc. The spacing between the two pairs of breakdowns is 8.33 ms, indicating the arc occurred at both the positive and negative peaks of the line-voltage waveform.

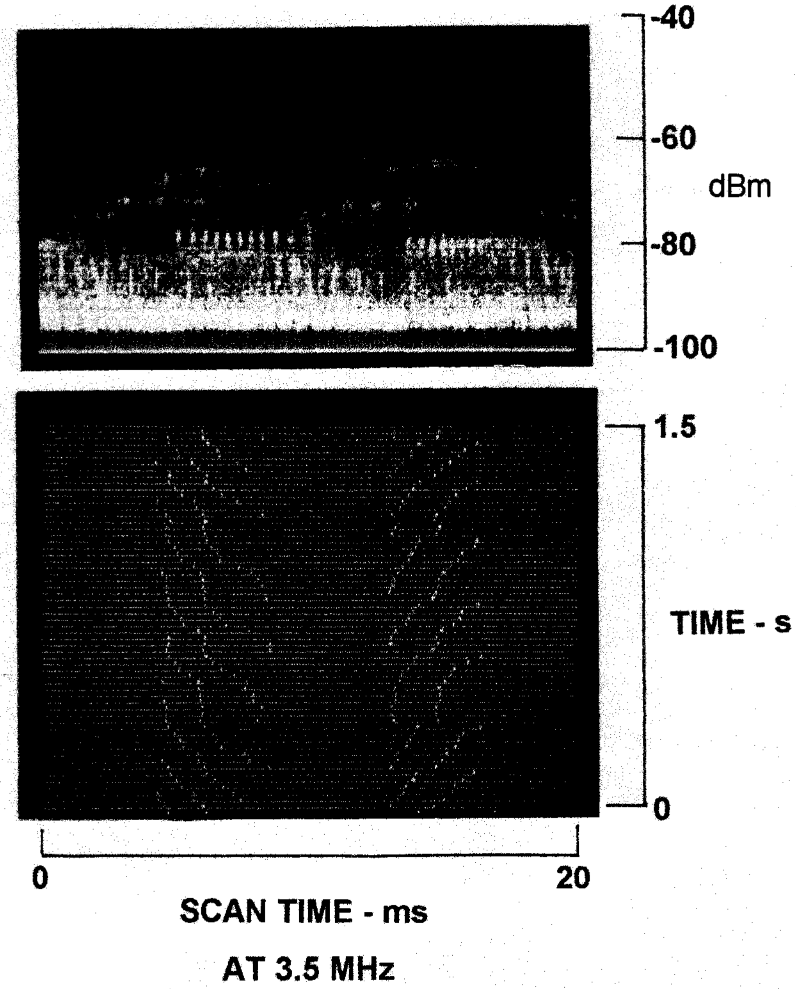


HAN, 959816, 1524, 3.5, 0, 30, 20(LS), LB 168, PD -3, BPF 1, 20, 0, -30
Source 9508-04, Phase C

Figure 15 Fine-Scale Temporal Structure, Example 4

Because the breakdown process of a small arc is usually quite erratic, the temporal structure will vary considerably with time and from one source to another source. Most examples will show the erratic timing of the initial pulse followed by one or two additional pulses, also with erratic timing.

In some cases the sparking process will produce well-defined temporal patterns in the time-history view. Figure 16 shows one such case where the timing of the pulses produced a distinctive pattern. The upper view shows that at least four sources of noise were present, but the threshold control for the time-history view was adjusted to permit viewing only the distinctive structure of the highest level noise. This allowed the site operator to concentrate on the highest-level noise before proceeding to the lower-level cases.



HUM, 930523, 1245, 3.5, 0, 30, 20(LS), P-225, BPF 1, 0, 0, -20

Figure 16 Fine-Scale Temporal Structure, Example 5

Figure 17 shows another example of the distinctive temporal pattern of sparking noise from the small arcing between the bottom threaded part of a pin insulator and its support bolt. The pin insulator had not been sufficiently tightened to form a solid metallic contact between the insulator threads and its mounting bolt. This allowed a thin insulating oxide layer to build up between the insulator threads and the mounting bolt resulting in a potential difference between the insulator threads and the mounting bolt.

Similar patterns can occur from other arcing sources.

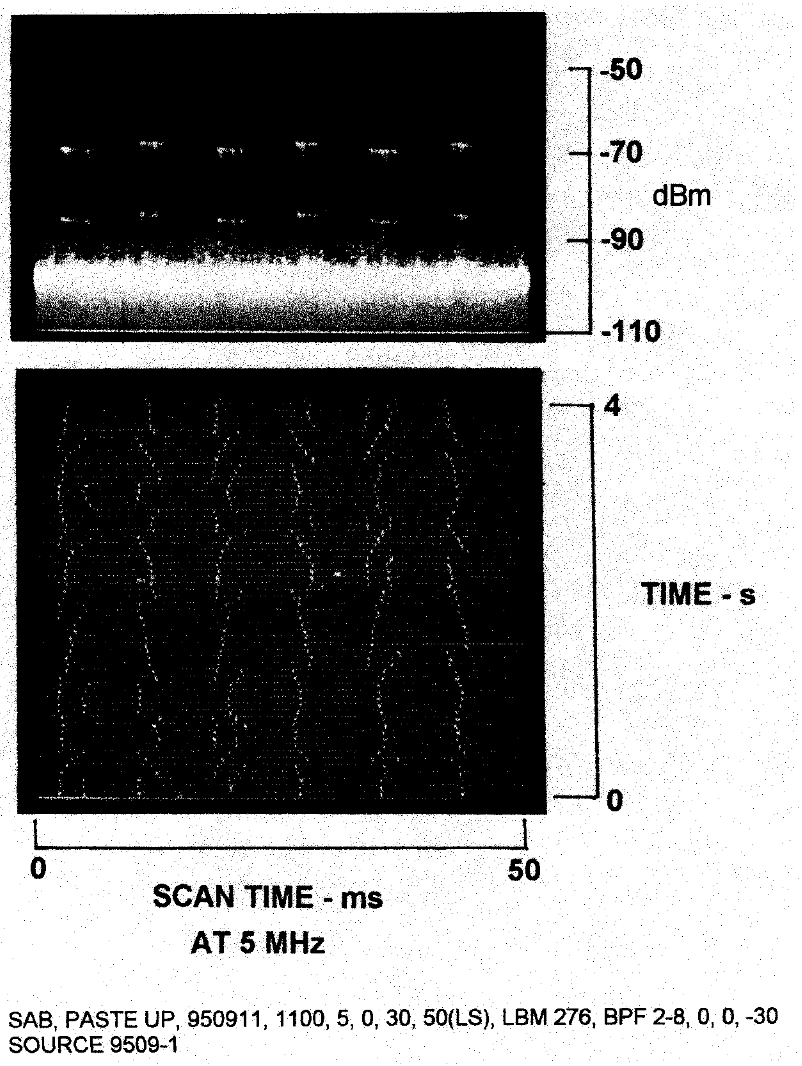


Figure 17 Fine-Scale Temporal Structure from a Small Arc

High voltage transients can be impressed on a distribution line during nearby or direct lightning strikes. Lightning arresters provide a path to ground to dissipate the charge buildup from a lightning strike, but their internal components can be damaged from a potent strike. The internal components of a damaged lightning arrester can then breakdown at the normal line voltage and at multiple locations within the arrester. The resulting overlapping arcing and microsparking can result in very potent radio noise at a receiver site located within line of sight of an overhead line associated with the source.

Figure 18 shows the temporal structure of radio noise from a damaged lighting arrester located several km from a receiving site. The temporal structure can be similar to that of a gap source, but the amplitude will not be quite as flat and the pulses will be usually be overlapping in time from multiple breakdowns. Lightning arrester sources are often more active at times of high humidity and often become inactive during times of low humidity.

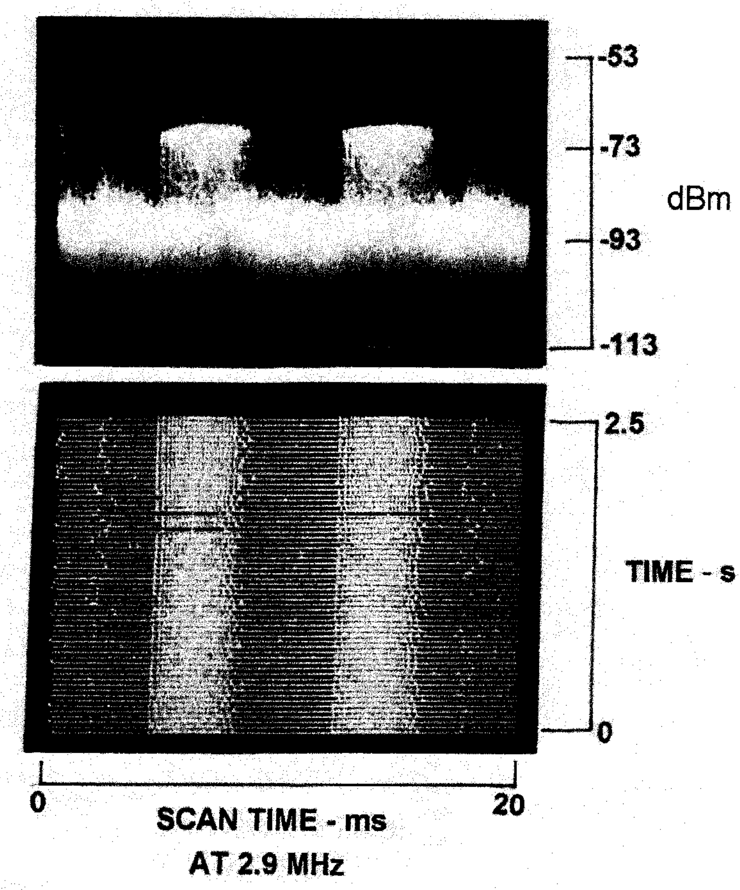
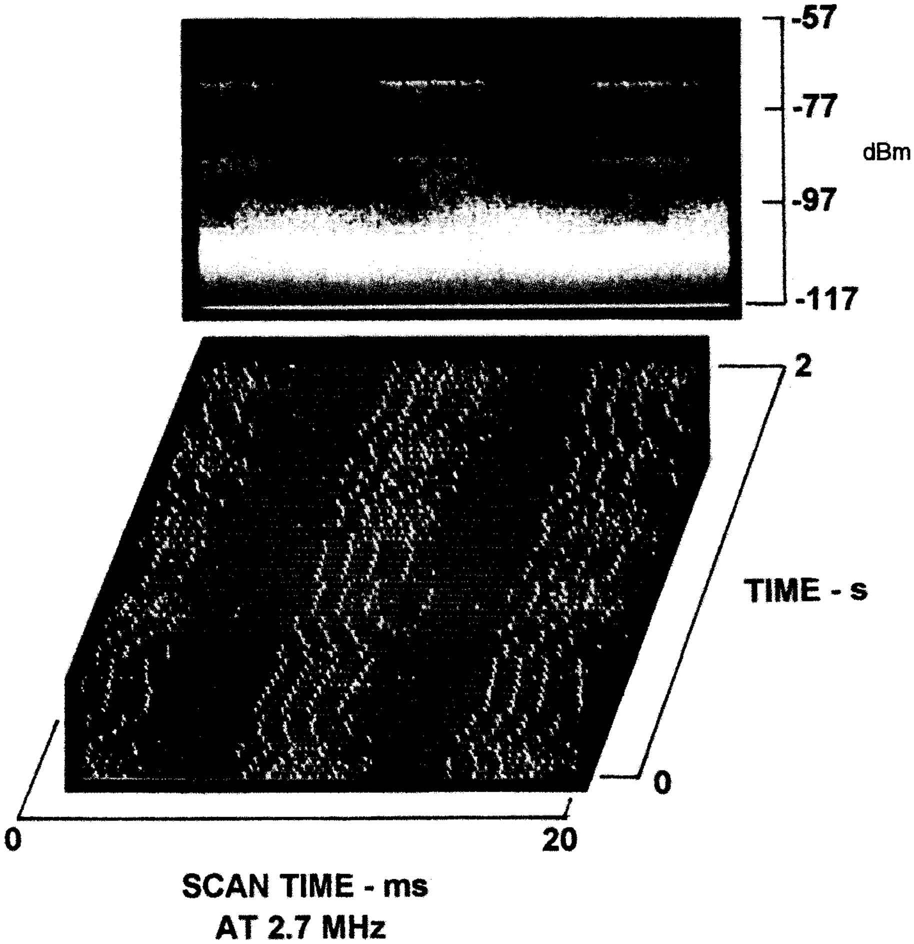


Figure 18 Fine-Scale Temporal Structure, Example 6

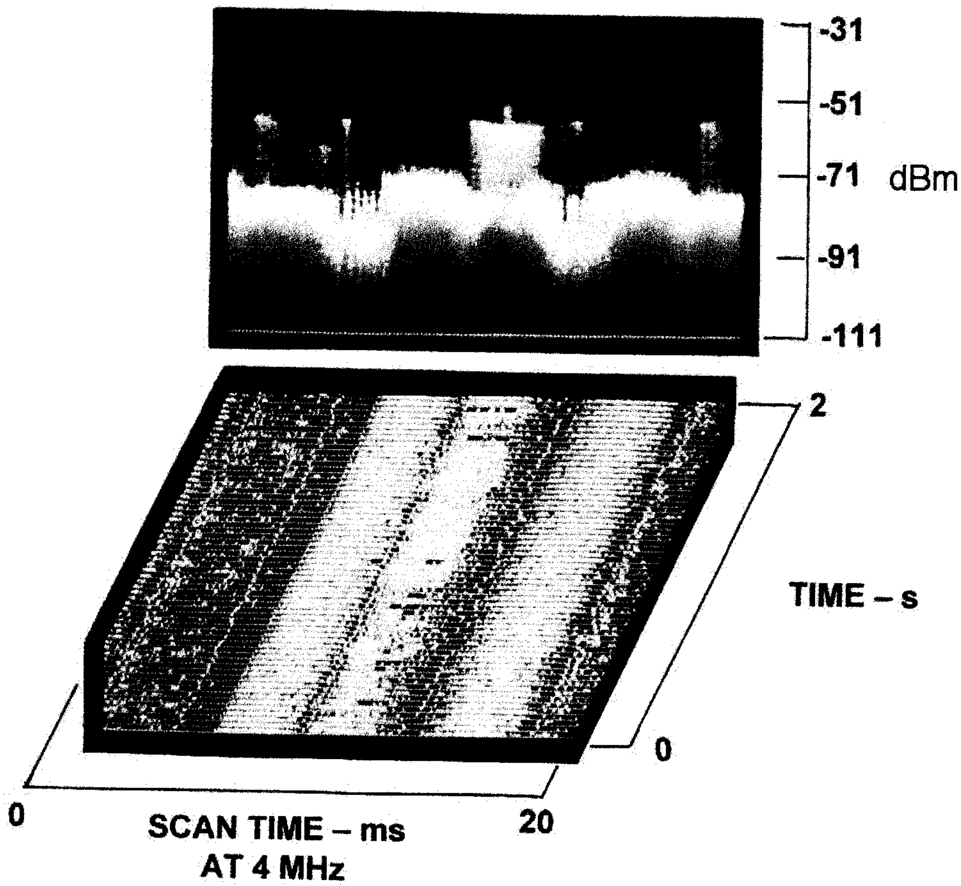
The distinctive temporal structure of Figure 19 suggests the source is probably different from the prior examples. A guy wire attached to a distribution line pole rubbed against other metal hardware and produced erratic microsparking that generated this complex temporal structure. The pole was about 2 km from the receiving site.



SAB, PASTEUP, 950919, 1030, 2.7, 0, 30, 20 (LS), LBM 288, PS (-3), BPF 9, 20, 0, -20
Source 9509-11

Figure 19 Guy Wire Rubbing Against Metal Hardware

The previous fine-scale views of radio noise from sources on distribution lines were obtained at times when only a single dominant source or a few sources were in operation. At times radio noise from multiple sources will be found, and the site operator must be able to distinguish between each source. Figure 20 shows an example of multiple sources. At least six and possibly seven sources are present. In this case, the site operator would place emphasis on the strongest sources, eliminate them, and then deal with the lower level sources.



ROT, 000913, 0940, 4, 0, 30, 20(LS 60), LBM 120, BPF 1, 11, 0, -20

Figure 20 Fine-Scale Temporal Structure, Example 7

2.5 Power-Conversion Devices

2.5.1 General Comments

Modern solid-state switching devices are used to alter electric power, control electric power, and change electric power from one form to another form. These devices are used in a wide variety of equipment and devices ranging from uninterruptible power supplies, switching power supplies, variable-speed controllers for electric induction motors, heating controls, light dimmers, solar power systems, and many other applications. Devices employing solid-state switching can place high levels of impulse current and voltage onto the electric wiring, ground conductors, and other metal components associated with a source. These impulses pass through the transformer providing power to a facility with little loss and onto the conductors of an overhead distribution line providing electric power to the facility. Noise radiating from the building conductors and the overhead power-line conductors of a distribution line associated with such a facility can result in severe radio interference at a radio receiving facility located within line-of-sight of the overhead lines providing electricity to a facility containing a power-conversion device. In some cases recent laws mandating the use of these devices in an attempt to conserve energy further exacerbate the noise problem at a receiving site.

The temporal and spectral content of the radiation is determined by the electrical design of the power-conversion device. The spectral content is further modified by the electrical impedances of its facility wiring, the electrical path from the facility to the overhead lines, and radiation from the overhead lines. While the temporal structure of a specific source is usually maintained and can be observed at a distant receiving site, the spectral shape of the broadband noise can contain deep nulls and peaks in amplitude caused by the electrical characteristics of the path between the source and the receiving site. However, the temporal structure can vary from one source to another, thus providing a means to distinguish one source from another.

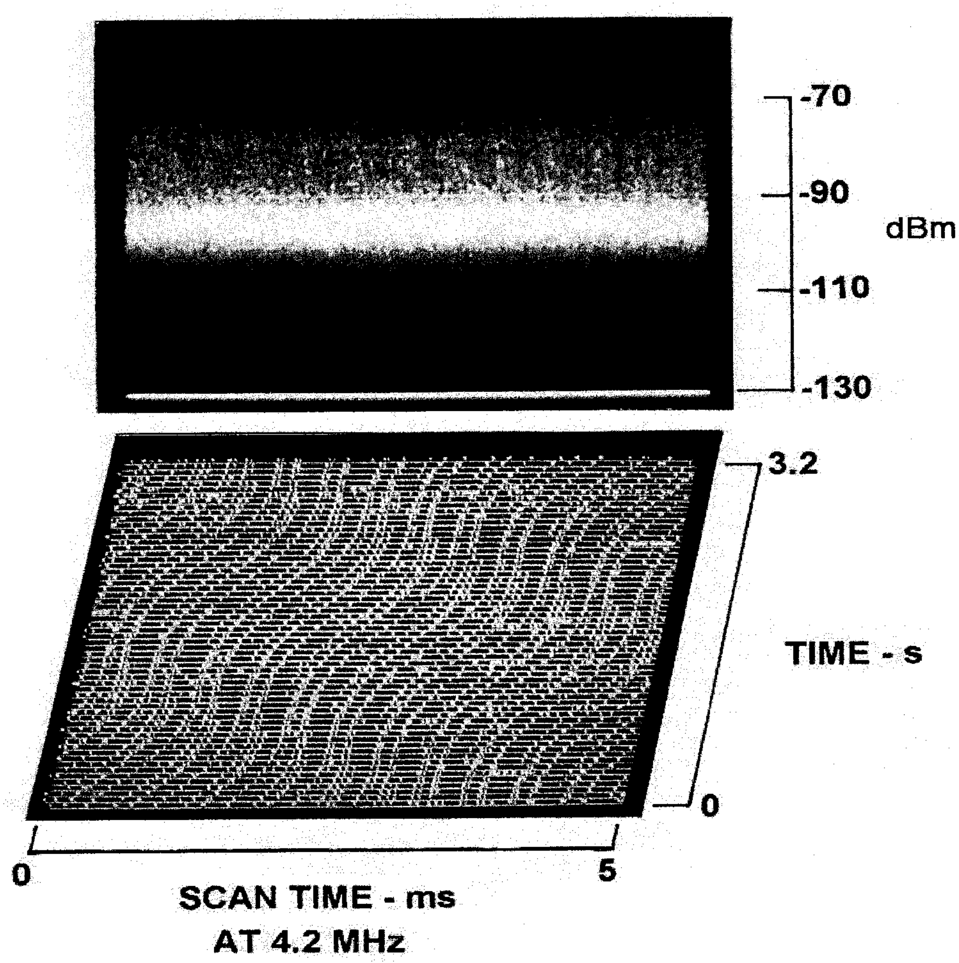
2.5.2 Variable-Speed Electric-Motor Drives

Variable-frequency power can be used to vary the speed of a standard induction electric motor where the motor size can vary from a fractional horse-power up to a multiple horsepower motor. Solid-state power-conversion devices are commonly used to change the fixed-frequency of electric power into a variable frequency power, thus providing a simple and effective means to change and control the speed of the motor. This technique can be used for a large variety of applications such as the control of the flow of air in facility, the speed of a conveyor belt, the flow of air into a ceramic furnace, and many other similar applications.

Harmful levels of radio noise from variable-speed drives were first encountered at a radio-receiving site in 1995. Since that time the population of such devices has dramatically increased due to their effectiveness, low cost, numerous applications, and new laws mandating their use. Since most such devices were intended for industrial uses, little attention was given to the impulsive current and voltage they imposed on the electric wires and other conductors in the facility housing these devices. While they generate sufficient noise to affect the reception of signals from AM/FM broadcast and television stations, the affected receivers were often within the facilities housing the power-conversion devices and under their direct control. However, radiation from the facility conductors and the overhead power lines providing electric power to such facilities extend far beyond the source facility. Any LF through VHF radio-receiving site within line of sight of the overhead power lines associated with such a facility is susceptible to radio interference.

Figure 21 shows an example of the fine-scale temporal structure of noise generated by a controller used to vary the speed of a fractional horse-power electric induction motor. This particular controller was located about 3 km from the receiving site.

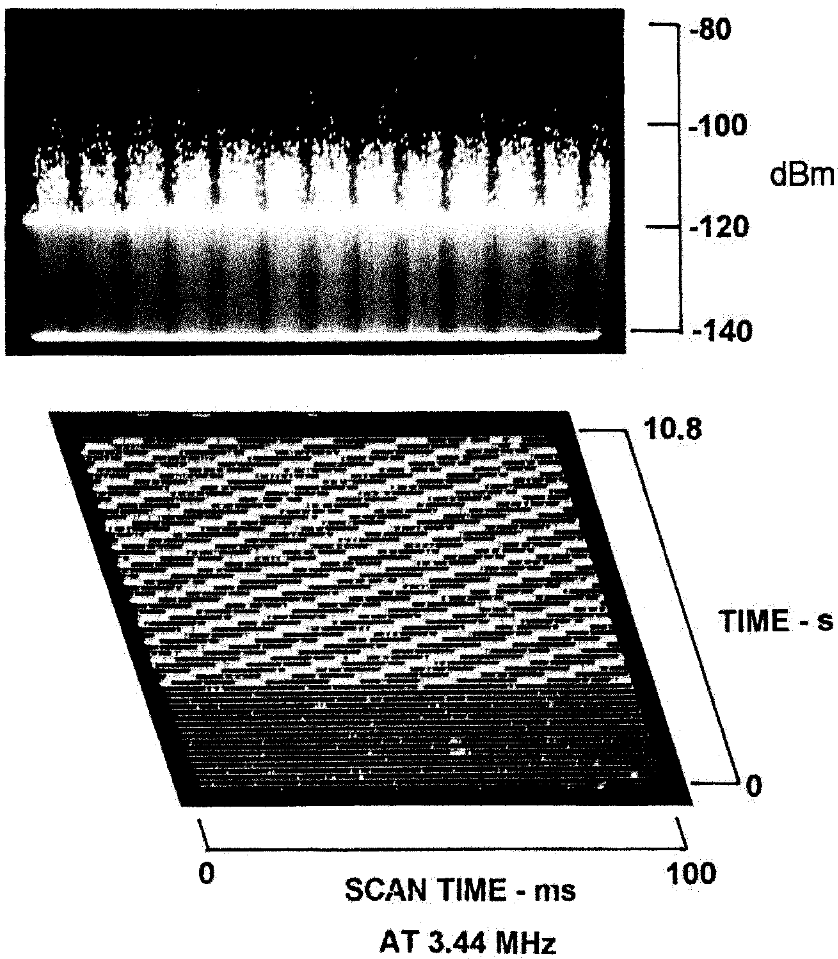
The data was obtained at the receiving site at a fixed frequency of 4.2 MHz to allow the time-varying temporal structure to be portrayed without encountering deep nulls and peaks in the spectral content of the data. The variations in the speed of the motor are clearly shown in the time-history view. The amplitude of the noise is considerably higher than the maximum amplitude of all signals of interest to the site.



HAN, PASTE UP, 950808, 1508, 4.2, 0, 100, 5, LBM 324, BPF 9, 20, 0, -30
Motor Controller Bravo

Figure 21 Fine-Scale Temporal Structure of Noise from a Motor Controller

Figure 22 shows the fine-scale temporal structure of noise from the variable-speed electric-motor drive used to rotate a VHF acquisition antenna a nearby VHF receiving site. The HF receiving antenna was about 1/2 km from the rotating antenna at the VHF site.



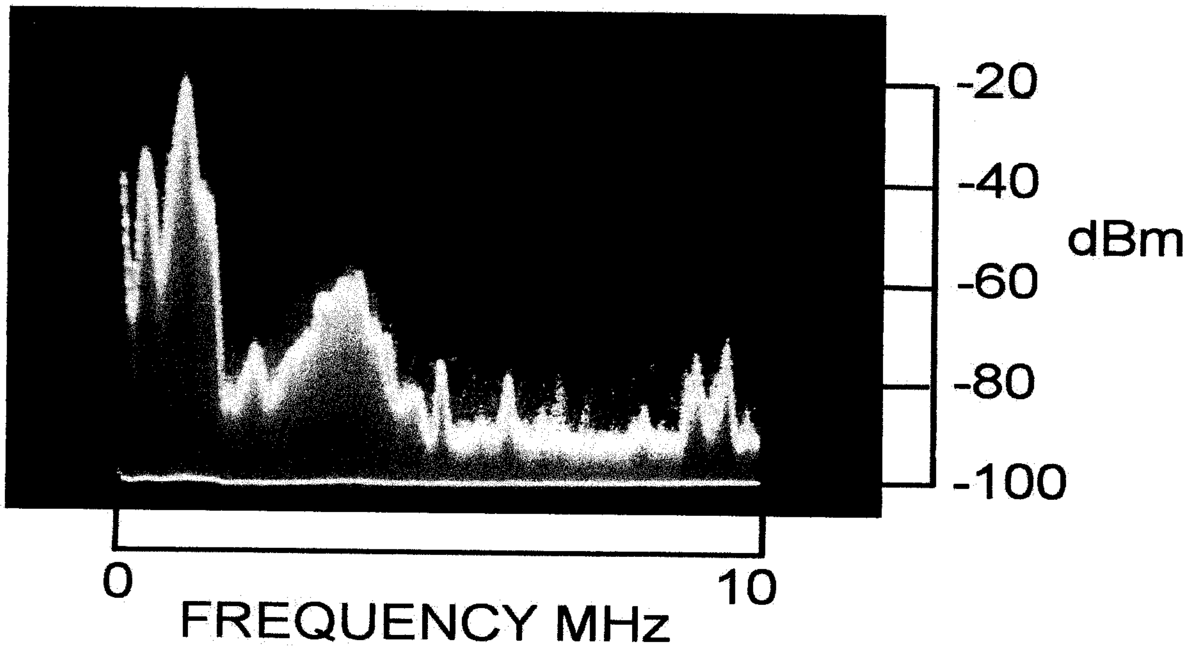
EDZ, 920514, 1043, 3.44, 0, 10, 100(LS), F-1, 20, 0, -40
Noise from controller of ACQ Antenna

Figure 22 Acquisition Antenna Controller Noise

The time-history view shows the antenna controller was operating during the upper part of the view, and it turned off about ¾ of the way down the view. Strong bursts of noise occurred at about 20-ms intervals. Since the scan process of the spectrum analyzer was synchronized to the frequency of the local power source, the slanting lines show that the controller operated at close to, but not quite, half the frequency of the local 50-Hz power.

2.5.3 Power-Conversion Device for a Residential Solar Power Installation

Solar- and wind power-generation systems use solid-state-switching devices to convert their power into a format compatible with other electric power systems. Figure 23 shows an example of the coarse-scale spectral content of noise from a direct-current to alternating-current converter used with a residential solar power system. The noise was recorded at a radio amateur's site located 1 km from the residence containing the converter. Very large spectral peaks and nulls of noise across the 10-MHz-wide band existed at the input to the radio amateur's receiver. These peaks and nulls prevent the use of a single amplitude value to characterize the noise, however noise amplitude can be provided at any specific frequency.

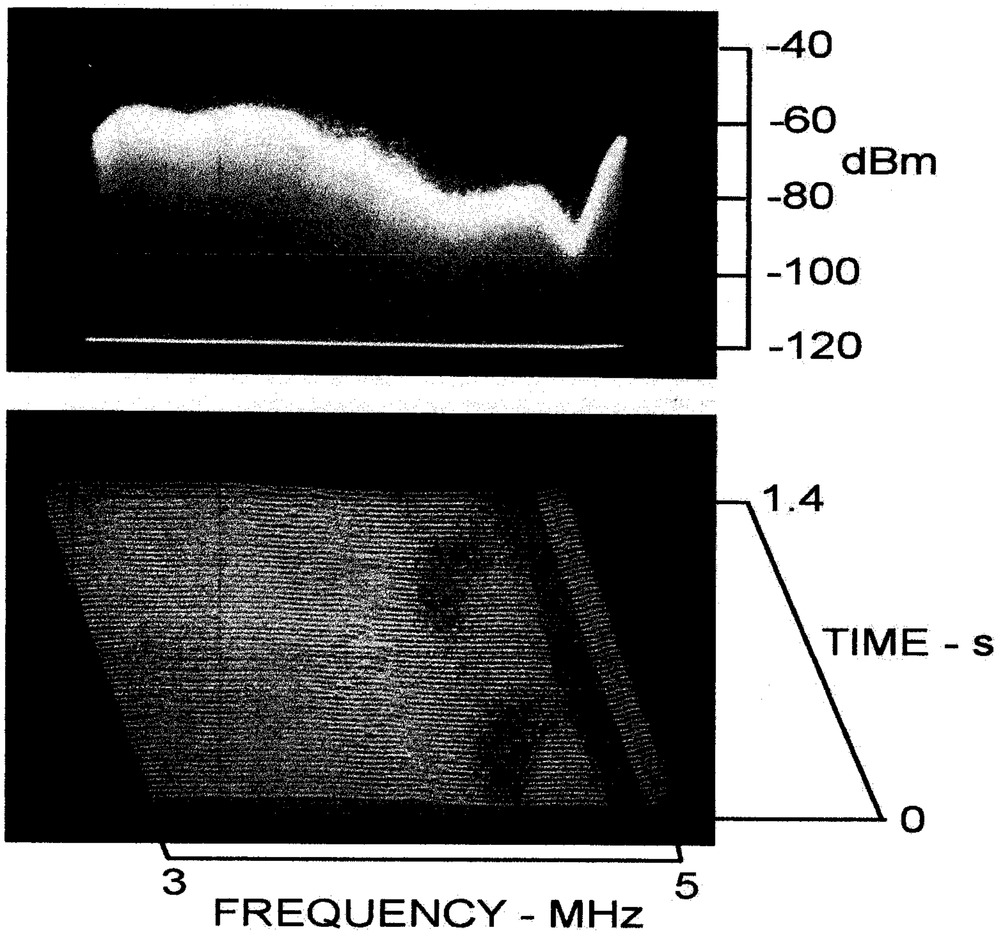


K6GDI, 030621, 1037, 5, 10, 100, 100(LS), 80 m DIPOLE, NF, 0, 0, -2

Figure 23 Solar Converter Noise at K6GDI

The residence with the solar converter was visited and measurements were made to determine the radiation mechanism. Current probes on the conductors between the converter and the house wiring indicated the broadband noise current was very low and radiation from the house wiring and the overhead power line feeding the residence could not explain the high levels of noise at the receiver location. A current probe on the DC conductors running from the converter to the roof-mounted solar cells indicated very high levels of conducted broadband noise. These conductors were about 50 meters in length, and they (along with the solar cell conductors) were the primary radiators of the broadband noise.

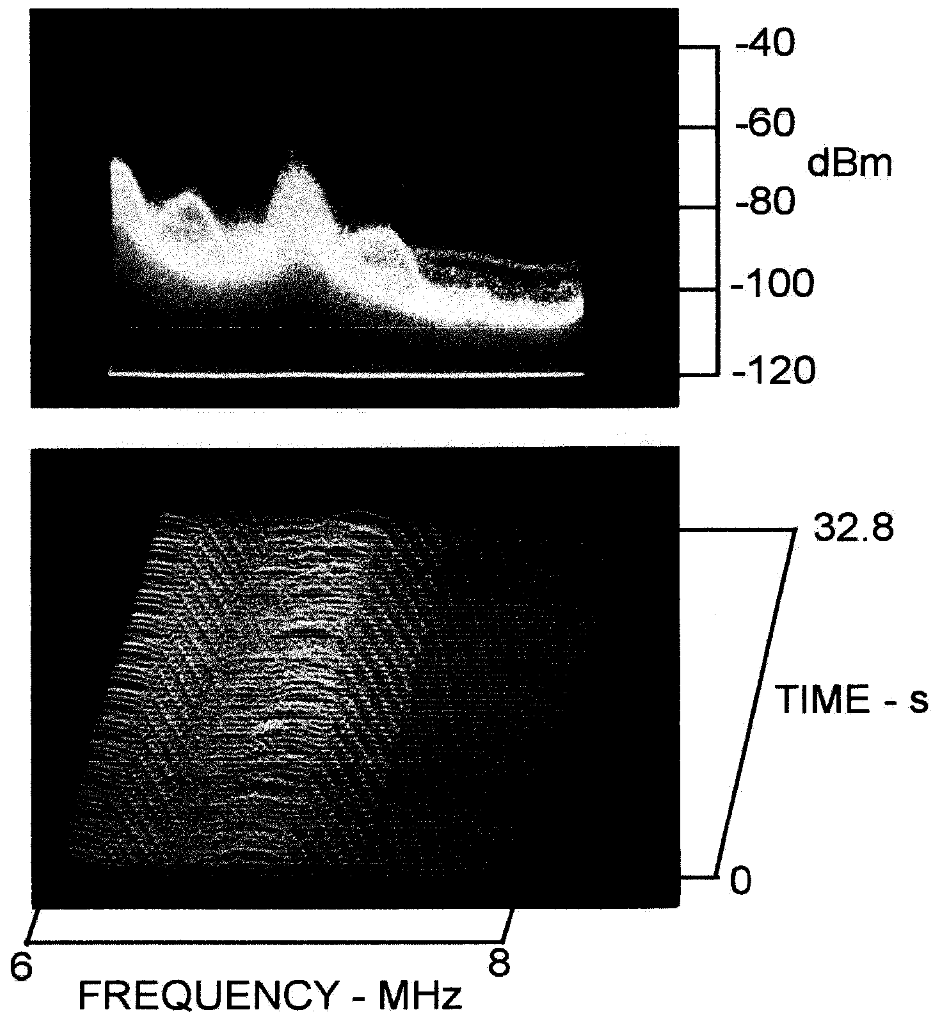
Since the radio amateur operator at K6GDI was the control station for a large-scale net operating on the 80-meter amateur band, the noise level in that band at his receiver input terminals was examined. The 80-meter band extends from 3.5 to 4 MHz, the center portion of the frequency range shown in Figure 24. The upper view shows the amplitude of the noise as delivered from his antenna to his receiver while the time-history view shows the noise was essentially continuous in time. While some temporal structure from impulses associated with converter switching is visible in the time-history view, its amplitude is nearly equal to the more continuous noise. The amplitude of signal levels during normal network operation range from about -130 dBm up to a high of about -80 dBm for single-sideband signals detected in a 3-kHz receiver bandwidth. The end result is that all signals from other stations in the network will be covered by the solar-system noise.



K6GDI, 030621, 1052, 4, 2, 100, 20, 80 m DIPOLE, F 2-8, 20, 0, -20

Figure 24 Solar Converter Noise at the 80-Meter Amateur Band

The amateur radio station also operated on 40 meters. A check of solar-converter noise at that band was also made. The 40-meter amateur band extends from 7.000 to 7.300 MHz, at the middle of the frequency range shown in Figure 25. The upper view shows significant peaks and nulls in noise amplitude across the frequency range shown. The two sets of slanting lines in the lower view show that repetitive impulses are present at two different rates. Apparently, the dc voltage from the solar cells was sampled at a different rate from the line frequency. Amateur radio operation at the low end of the band is not feasible, and only a few exceptionally strong signals will barely exceed the noise level at the upper edge of the band.



K6GDI, 030621, 1043, 7, 2, 100, 500, 80 m DIPOLE, F 2-8, , 20, 0, -20

Figure 25 Solar Converter Noise at the 40-Meter Amateur Band

2.5.4 Uninterruptible Power Supply

Some radio-receiving sites are located close to other facilities. In one case a satellite communications terminal was located about 1 km from an HF and VHF receiving site. The satellite terminal was equipped with an Uninterruptible Power Supply (UPS) to allow it to continue operation during short-duration power outages. The site was also equipped with diesel-powered generators for longer periods of power failures.

When the satellite terminal was placed into operation, a new radio noise source appeared at the HF site. Figure 26 shows the temporal and spectral properties of the new interference that was traced to the UPS in the satellite terminal. The slanting lines represent impulses from the switching process of the power-conversion devices in the UPS. The UPS noise made it impossible to receive the low-level ambient signals that are also shown in the example.

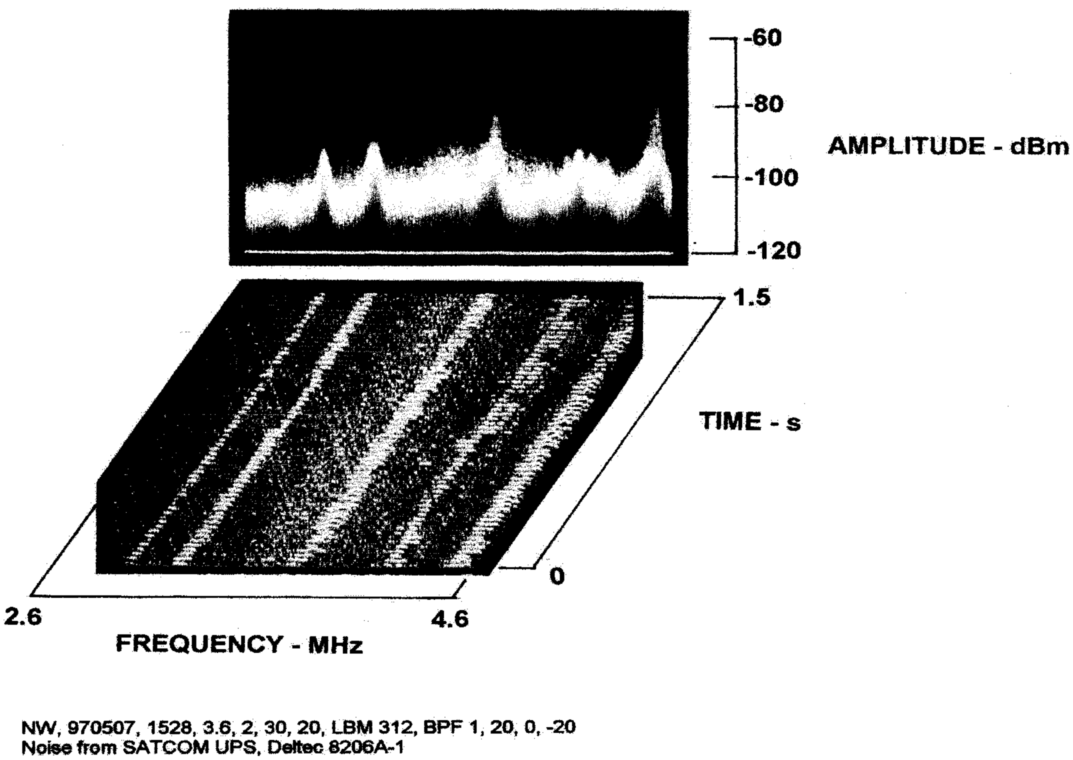


Figure 26 Interference from a UPS Located 1-km from a Receiving Site

An additional and even more potent noise source affecting other parts of the HF spectrum was also traced to the new satellite communications facility. In this case the noise was traced to a second power-conversion device that was used to control the field current in the diesel-powered generators. Neither the UPS nor the power-conversion device caused harmful interference at the microwave frequencies used by the satellite terminal, but they did cause harmful levels of interference to the nearby, but separate, HF site.

2.6 *Other External Sources*

2.6.1 General Comments

A noise investigator will encounter a number of additional sources of noise external to a receiving site in addition to those associated with hardware on power lines or from power-control devices. Knowledge of other sources and the temporal and spectral properties of their noise are essential to avoid the high cost and excessive time of false location, identification, and mitigation efforts.

2.6.2 Ignition Noise

In past years ignition noise from automobiles and trucks with gasoline engines was a prominent problem. In some cases the use of automobiles was restricted near antennas and other special precautions were taken to avoid ignition-noise problems. These precautions often included special equipment to monitor ignition-noise levels of automobiles as they approached a site. Quiet vehicles were allowed access to a site, but noisy vehicles were denied access.

With recent improvements in the design of ignition systems for gasoline motors and the compliance of automobile manufacturers with modern radio-noise standards, vehicular radio noise has almost, but not quite, been eliminated. Modern automobiles can usually be operated close to the antennas of a receiving site with very little or no problem. Only older automobiles and trucks, those with modified ignition systems, those with faulty ignition systems, motorcycles, and other small vehicles are now of concern. Fortunately, the population of such vehicles is low, and only minimal effort is required to identify noisy vehicles and restrict their use near a receiving site.

In addition, special gasoline-powered vehicles and other devices exist that radiate excessive ignition noise, and they are sometimes used in the vicinity of receiving sites. Devices such as weed whackers, lawn mowers, small utility vehicles, gasoline-powered electric generators, diesel-powered electric generators using electronic power control and power conversion, and other similar equipment are often major sources of radio noise. Such vehicles and devices are not required to meet the noise limits imposed on automobile and truck manufacturers. Their use at and near receiving sites must be strictly controlled.

Older diesel-powered vehicles were exceptionally noise quiet, but modern diesel engines have electronic powered injection and fuel-control systems. The current impulses on conductors in these systems result in excessive noise levels similar to ignition noise, and most of today's diesel-powered vehicles are unsuited for use in and around radio receiving sites.

Yet one more source of radio noise can be traced to modern devices. Most late model portable electric generators (either gasoline or diesel powered) provide direct-current electrical power. Power-conversion devices are used to convert the electric power into 50-Hz or 60-Hz alternating power at 120/240-V or other desired voltages. Impulsive noise from such generators renders them unsuitable for use on and around radio receiving sites unless they are especially modified to reduce impulsive noise to harmless levels.

Figure 27 shows an example of ignition noise observed at a receiving site. The curved pattern of the noise impulses is caused by the changing rotation rate of the engine. The time between impulses from the ignition system changed with the engine rotation rate. The variable timing of the impulses interacted with the slower (but constant) scan time of the spectrum analyzer used to receive the noise. The source of this example was a single-cylinder motorcycle.

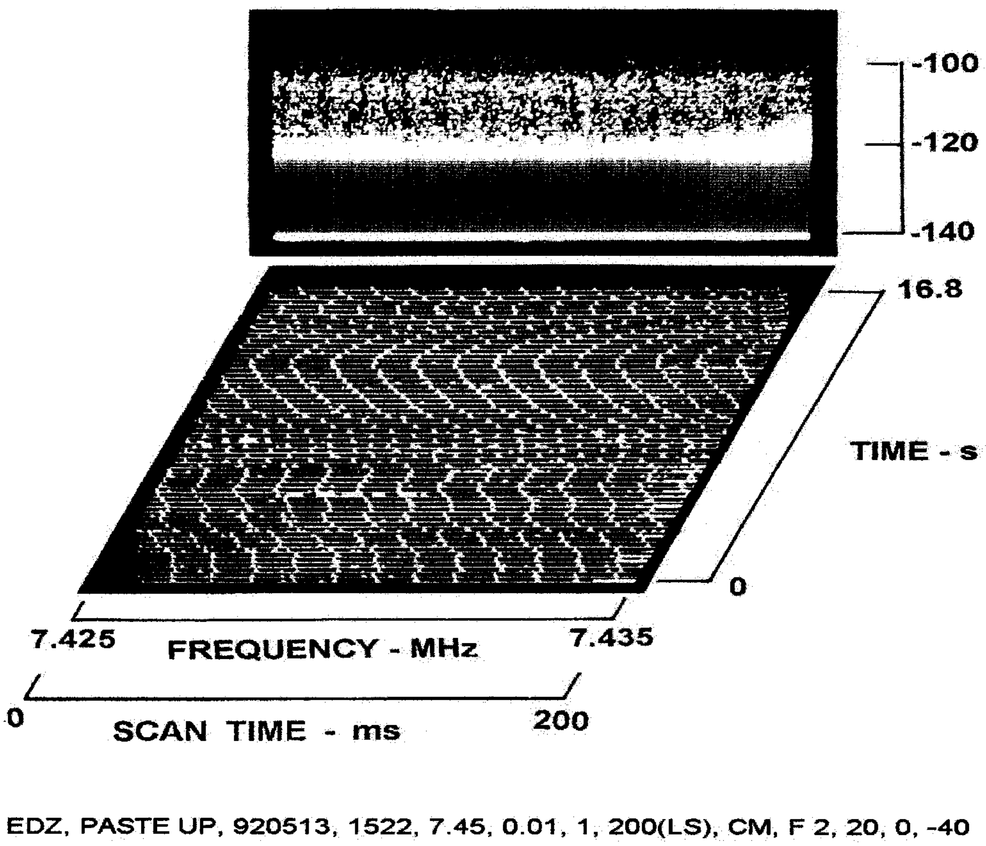
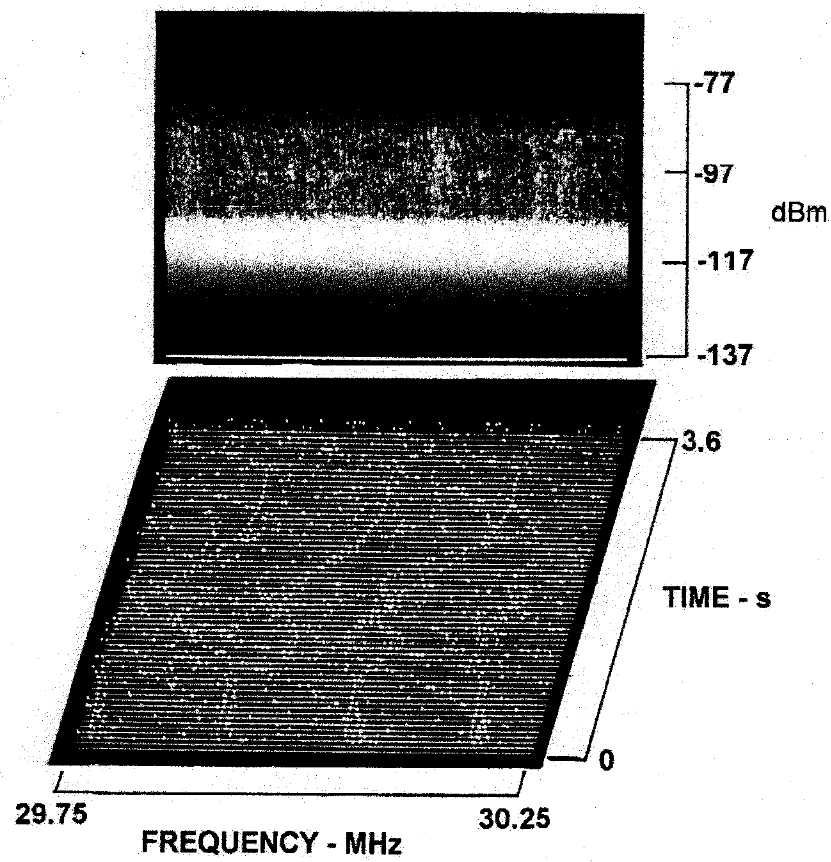


Figure 27 Temporal Structure of Ignition Noise

Figure 28 shows the fine-scale temporal structure of radio noise from the small gasoline engines of multiple weed whackers. The weed whackers were trimming grass and weeds around the antennas of a receiving site, and they induced impulsive noise into the ground plane of the receiving antenna. The smoothly changing pattern of the impulses from the more prominent sources can be seen in the time-history view. Normal receiving tasks could not be accomplished at this site while gardening work was underway.



HAN, PASTE UP, 950808, 0940, 30, 5, 30, 50, HBM 96, PS(-3), HPF 25, 20, 0, -40

Figure 28 Temporal Structure of Noise from Multiple Weed Whackers

2.6.3 RF Stabilized Arc Welders

RF stabilized arc welders use radio-frequency power in the medium-frequency band to establish an arc, but the RF arc produced by the medium-frequency does not penetrate metal sufficiently for welding. RF-Stabilizers start an arc with a radio-frequency and then apply alternating current to the arc at the power-line frequency in parallel with the radio frequency. The combined arc from both radio-frequency and 60-Hz power is very stable and penetrates metal sufficiently for welding. Such arcs are widely used to weld Aluminum and other metals. Unfortunately, these devices feed harmonics of radio-frequency and the power-line frequency along with intermodulation products of both frequencies onto the electric-power wiring of a facility and onto overhead power lines supplying electric power to the facility.

Figure 29 shows an example of severe radio noise from an RF-stabilized welder recorded at a receiving site. The RF stabilized welder facility (making aluminum fishing boats) was more than 11 km from the receiving site.

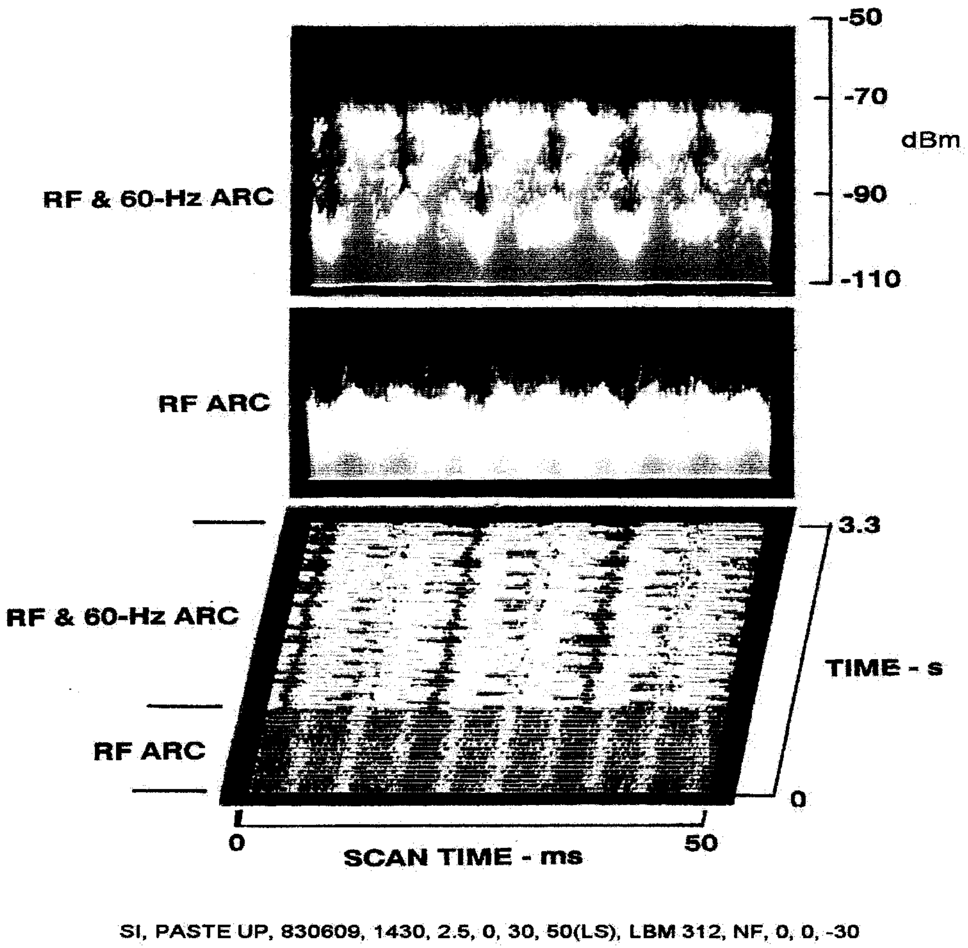
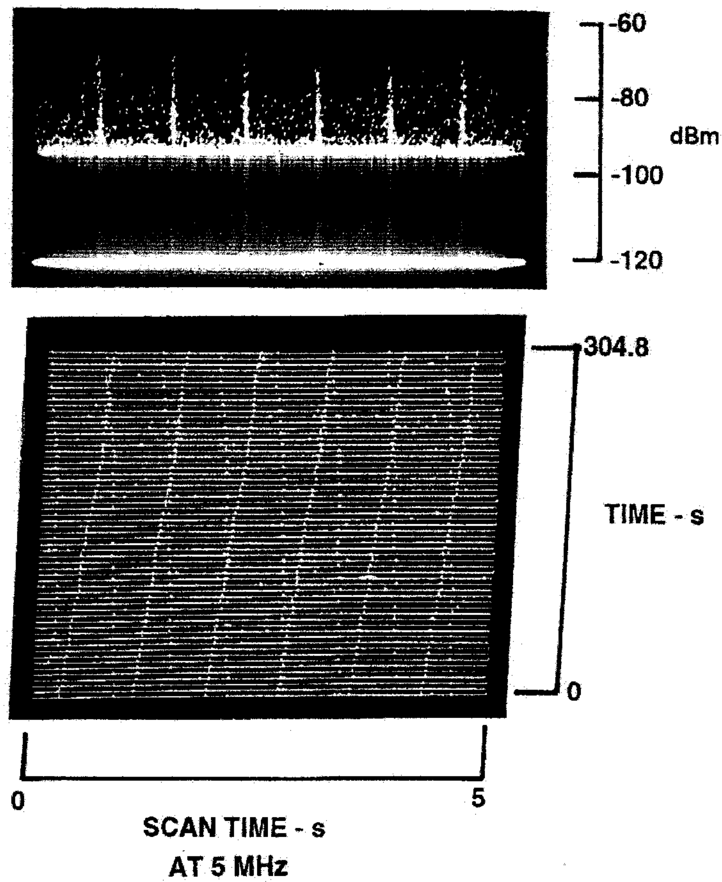


Figure 29 Noise from an Industrial RF Stabilized Welder

2.6.4 Electric Fences

Electric fences are often used in the rural areas surrounding receiving sites. Some electric-fence controllers inject significant levels of pulse voltage and current into the fence conductors, and the electrically long fence wires are efficient radiators of broadband impulsive noise.

Figure 30 shows an example of pulses from two fences as received at a receiving site. In this case the noise was received on a 20-ft length of television mast material that was used for a test antenna at a receiving site. The noise peaks, spaced roughly 1-second apart, produced very strong impulses in the receiver. The fences were more than 1 km from the receiving site.



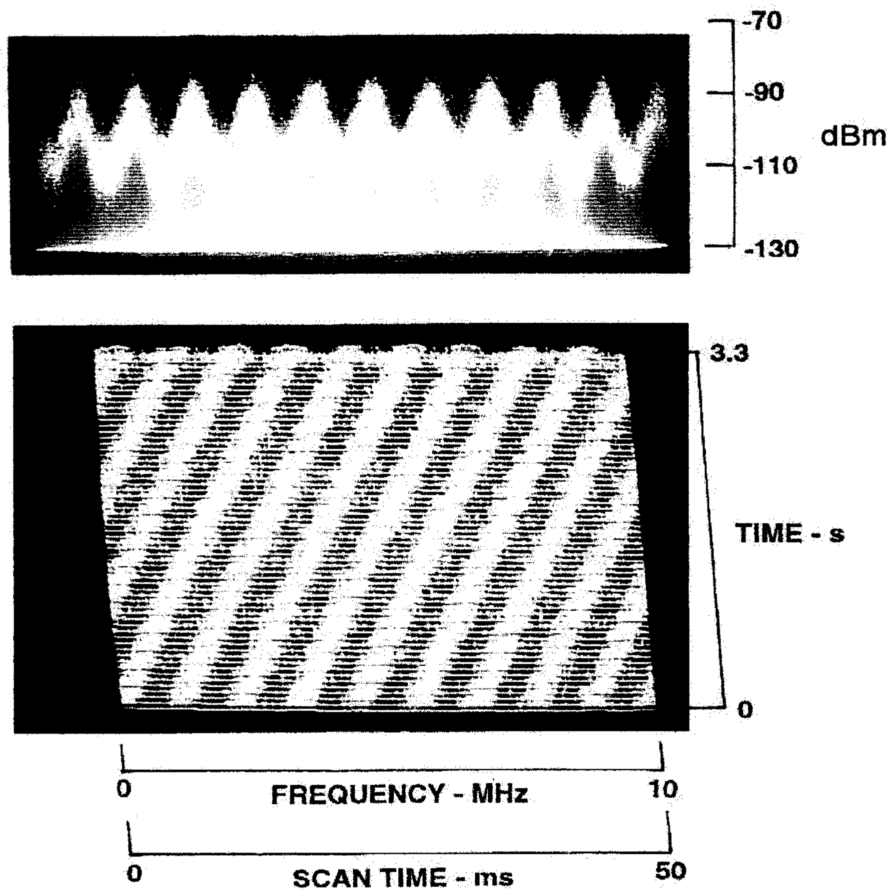
EDZ, 910911, 1530, 5, 0, 10, 5000, 20-FT PIPE, BPF 2-8, 20, -20, -20

Figure 30 Noise from Two Electric Fences

2.6.5 Corona Noise

Corona noise is sometimes observed at a receiving site. It is not included in the earlier descriptions of noise from primary sources because corona noise sources exist only on transmission lines operating at high voltages (typically from 69 to as high as 750 kV and in some special cases up to 1 MV). The lower voltage levels used on distribution lines (from 1.2 to about 35 kV) will not support the air breakdown process of corona-noise sources.

Figure 31 shows the temporal structure of corona noise. Each burst contains a vast number of overlapping impulses where the amplitude of each individual impulse is a function of the line voltage. The rounded shape of each noise burst is typical for corona noise. In this example, the scan process of the analyzer was not synchronized to the power-line frequency, thus slanting lines were formed in the time-history view.



SI, 910814, 1535, 5, 10, 10, 50, 3m, NF, 20, 0, -40

Figure 31 Corona Noise

The source of the corona noise in Figure 31 was identified as the breakdown of air at very small and sharp metal protrusions that formed on the upper side of the arm of a high voltage switch in a substation operating at 135,000 volts. The substation was located about 2 km from the receiving site. When these small protrusions were removed the corona noise disappeared.

2.6.6 Broadband over Power Lines

Recently radio amateurs and other organizations have experienced severe radio-noise problems from Broadband over Power Lines (BPL). The authors of this document have not encountered noise from BPL at the many radio receiving sites where extensive noise measurements were made (more than 45 sites worldwide). This is because BPL was not used on overhead-power lines within line of sight of any of the sites at the time of the visits.

Since the receiving sites of concern are designed to detect and receive very weak signals operating with a variety of modulation formats, available evidence clearly indicates BPL will be a major source of radio noise and radio interference if implemented on power lines within line of sight of a radio receiving site. Serious degradation in signal detection and signal reception is expected if BPL is used on power lines within line of sight of a receiving site.

Of special concern is that BPL operates in an environment which contains nonlinear equipment, devices, and contacts. This enhances the possibility of the production of harmonics, intermodulation products, and intermodulation noise at higher and lower frequencies than used by BPL. While such spectral components may be low in amplitude compared to the normal interference experienced by BPL and some receiving sites, such interference can be of significant concern to more specialized receiving sites.

<u>This major new source of radio noise and interference needs to be carefully examined by site planners, site managers, and site operators as well as by organizations managing the radio spectrum</u>. Means to prohibit the use of BPL at or near present or possible future radio-receiving sites must be implemented, and a means to deal with any existing BPL system already installed at or near a radio-receiving site needs to be implemented.

3. Step 2—EXAMPLES OF SOURCE DEVICES

3.1 Power-Line Sources

3.1.1 General Information

A detailed knowledge of power-line hardware and noise-production mechanisms on distribution and transmission lines is essential to locate, identify, and mitigate sources of radio noise on power lines. This is a difficult and time-consuming process for a number of reasons. Power-line hardware is considerably different from that normally encountered in receiving sites, thus personnel at such sites will not be familiar with the hardware or noise sources. Also, the hardware varies from country to country, electric utility to electric utility, and even within the territory served by an electric utility. Electric-utility linemen and radio-noise specialists go through several years of apprenticeship training to become acquainted with the vast variety of hardware, line-construction standards, line-construction procedures, noise-generation mechanisms, and safety procedures before they are considered proficient in power-line maintenance and radio-noise mitigation. This kind of experience cannot be obtained from this handbook. This handbook is only an aid in the process of gaining the required experience.

The prior section has indicated that two basic sources exist on electric-utility distribution lines. These are microsparking from the breakdown of very thin layers of insulation oxide found on the surface of metal hardware, and sparking from the breakdown of air between two pieces of metal or from one charged object to another charged object. In microsparking, the spark is very small (as small as 0.002 cm) and generally invisible. Sparking sources can be as short as a fraction of a cm or up to about 2-cm long. The common characteristic of these two mechanisms is a step-function in current flow which generates almost infinite spectral components. These two mechanisms can be associated with a variety of hardware on distribution lines. A third source, corona noise, occurs from the breakdown of air around a conductor, and it is found only on transmission lines.

Table 1 lists the most common items of hardware on electric-utility distribution lines that have caused harmful noise at radio receiving sites. Only six sources appear on this short list.

Table 1 Most Common Sources

Source Hardware	Rating
Bell Insulators	1
Loose Hardware	2
Lightning Arrester	3
Insulated tie wires on either bare or insulated conductors and bare tie wires on insulated conductors	3
Arcing between inadequately spaced and unbonded metal components	3
Improperly assembled transitions between overhead conductors and underground cables	3

A number of less-common sources have been encountered during noise-mitigation work at receiving sites and during other source-identification tasks. Table 2 lists these sources.

Table 2 Other Sources

Sources
Loose crossarm brace
Loose crossarm bolts
Loose transformer bolts
Loose insulator on a pin bolt
Loose insulator bolt on a cross arm
Loose staples on a bond or ground wire
Bond or ground wire too close to hardware
Loose tie wire
Bad connection on a primary or secondary conductor
Less than 1½ inch spacing between hardware not bonded together
Loose saddle clamp on insulator
Carbonized rubber saddle pad with a pin or post insulator
Broken or flashed insulator
Failure of transformer insulator
Twisted wire connections
Loose split bolts
Loose aluminum conductor connections
Insulated tie wire on insulated conductor
Broken bond or ground wire
Tree branches touching primary guy wire above Johnny Ball
Tree branches touching primary conductor
Slack or broken guy wire
Guy wire touching another guy wire
Guy wire touching a metal object
Guy wire touching telephone, CATV, or TV cable
Guy wire touching telephone, CATV, or TV cable messenger wire
Loose switch contacts
Loose switch mounting bolts
Loose fuse contact between fuse and fuse holder

* The authors of this handbook are grateful for the help of several utility radio noise specialists in compiling this list of sources. We are especially thankful for the help of Mr. Wally Hanifin (now retired) of the Pacific Gas and Electric Company.

Of interest is that some hardware items often thought to be common sources are not on the two lists. Examples are aging of hardware, corrosion, and dirty insulators. None have been identified as sources on distribution lines during the field work associated with this handbook.

3.1.2 Bell Insulator

Many sources of radio noise have been traced to the bell insulator. Figure 32 shows a two-section bell insulator used on distribution lines. Single, dual, and triple bells are commonly used on distribution lines operating at 10- to 40-kV phase-to-phase or phase-to-ground potentials. Single bells are commonly used on lines operating at voltages of 13 kV or less.

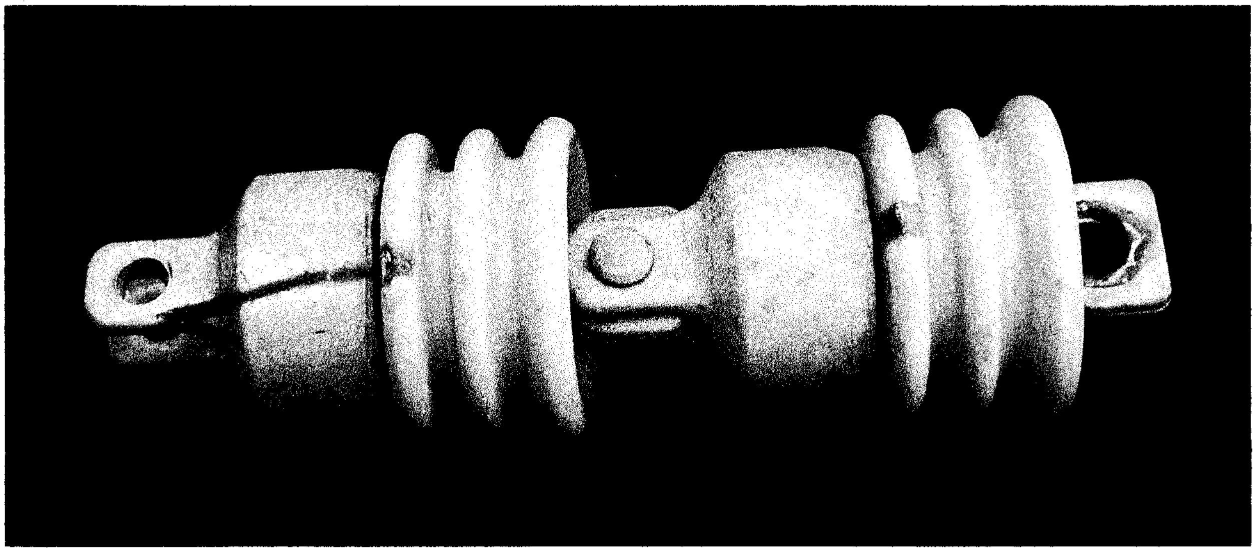


Figure 32 Bell Insulator

The bell insulator is rugged, has a long life (typically 40 years or longer), does not significantly deteriorate with exposure and age, retains its insulation properties with age, normally tolerates flashovers from lightning, and is inexpensive. These desirable properties have made the bell insulator a popular item with many utilities and public works departments. Yet, the bell insulator has gradually been recognized as a major source of radio noise. Because of this, some utilities are now using other types of insulators to replace bells.

About 1 out of 100 bell insulators is a source of radio noise at a radio-receiving site. The reasons why one particular bell insulator becomes a source of noise are obscure and not well understood. Visual inspection seldom reveals a flaw or any other reason why one bell generates noise and many others do not.

The particular bell insulator shown in Figure 32 was removed from service because of lightning damage. A long burn mark is visible on the metal portion of the left section along with a short streak on the left rib of the left porcelain insulator. Another short streak is visible on the first rib of the porcelain at the right end of the bell. In addition, the clevis on the right end of the insulator shows burn damage around its hole. These visible marks on the insulator were caused by a flashover from a direct lightning strike. Apparently the flashover jumped over the center of the insulator.

The burn marks did not result in radio noise, and thus were of no concern to noise-mitigation personnel or to the operation of a nearby radio-receiving site. The decision to replace such a bell, if it is not a source of noise, should be left to personnel of the electric-utility or public-works organization operating the line.

The primary source of bell-insulator noise has been traced to the electrical breakdown of a thin layer of oxide that forms on the surface of the metal parts of the insulator. The breakdown process is complex and has been extensively investigated by Beaseley[2]. The oxide-layer breakdown can occur at any of several locations on the bell. The locations are the clevis-pin joining connecting the sections of a bell, the end connection to the supporting pole, and the connection to the line conductor.

To better understand the noise-generation mechanism, an equivalent electrical circuit of a two-section bell has been developed. Figure 33 shows a sketch of a bell and the equivalent circuit. Each component of the equivalent circuit is located immediately below the corresponding part of the insulator.

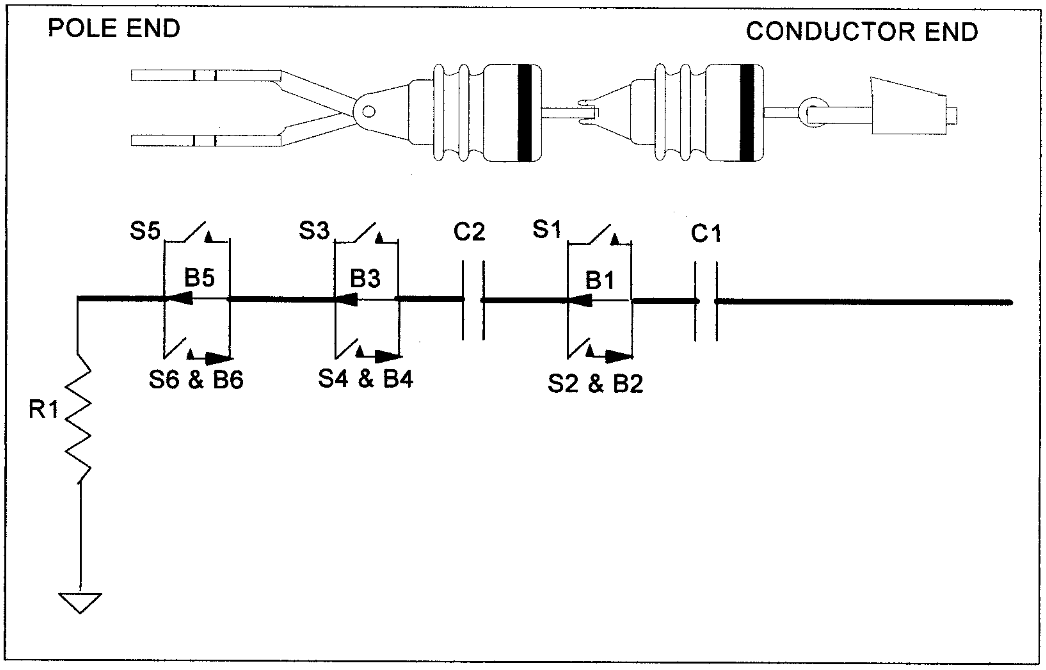


Figure 33 Circuit Diagram of a Bell Insulator

The equivalent circuit can be modified to fit a one-, two-, or three-section bell insulator. A two-section bell was chosen for the example since it is the most common configuration found on distribution lines. C1 is the capacitance across the ceramic, or glass, insulation of the section near the hot line. This capacitance is considerably larger for a bell type than other types of insulators because of its internal construction. The metal line-attachment component extends inside the ceramic or glass insulation material and inside the metal component of the opposite side. The two metal components and the high dielectric constant of the insulation material

[2] William L. Beaseley, An investigation of the Radiated Signals Produced by Small Sparks on Power Lines, Ph.D. dissertation, Texas A&M University, January 1970

produce the relatively high capacitance across each section of a bell insulator, and this capacitance is one of the factors involved in noise generation. Typical values of capacitance across a section of a bell insulator range from about 35 to 45 pf. This capacitance is sufficient to provide significant capacitive transfer of electric charge from the hot line to right side of the insulator that is opposite in phase to the potential of the line.

S1 is closed if the clevis pin between the two sections provides a conducting connection. When S1 is closed, that portion of the bell will not generate radio noise. It is open when the two sections of the insulator are separated by a thin layer of insulating oxide.

If S1 is open, then B1, S2, and B2 must be considered. B1 is shown as an arrow pointing left. This represents the insulating oxide layer between the two metal portions of a bell insulator. A charge transfer occurs in one direction across the thin layer of oxide when the oxide breaks down. The arrow indicates the transfer of charge during the positive portion of the line-voltage waveform. A potential of about 800 to 900 volts across the insulating oxide layer will cause it to break down.

If S1 is open, S2 may be open or closed. If S2 is open, a potential cannot be induced across B2 on the negative portion of the line-voltage waveform. If S2 is closed, then the insulating layer, B2, can break down on the negative half of the line-voltage waveform. This produces a second set of breakdowns, separated in time from the positive set by one half the period of the line-voltage waveform.

The charge transfer across B1 and B2 produces a brief pulse of current with a magnitude of about 7 to 9 amperes. This burst of current equalizes the potential on each side of S1 which terminates the oxide breakdown and the flow of current. The charge may then build up and repeat itself for one to twelve more times during each positive portion of the voltage waveform and also for the negative portion of the voltage waveform when S2 is closed.

If S1 is closed by a good electrical connection at the interconnecting clevis pin, the potential appears at the left side of the second bell section. This results in a transfer of charge through C2. If S3 is open, the potential difference appears across oxide layer B3. It can break down in manner similar to the process described for B1. If S4 is closed, another breakdown can occur at the opposite portion of the line-voltage waveform and produce a second set of impulses.

If both S1 and S3 are closed, a potential appears across the oxide layer on the clevis-pin joint on the insulator-to-post support hardware. A similar breakdown process can then take place at B5 and B6. The transfer of charge across C1 and C2 will result in a micro spark at B5 and B6 only if the pole-to-ground resistance is very high.

All of the oxide layer breakdown conditions and locations described have been identified during power-line noise-mitigation efforts. Since the insulating oxide layer is only about 0.001 to 0.01 inch thick, the breakdown process cannot be considered an arc or even a spark. It is called a *micro spark* in this document. The charge transfer process across the B elements is similar to the reverse breakdown process in a diode, commonly called a charge avalanche process.

Still another factor must be considered in the bell-insulator noise-mechanism process. An overhead distribution line is an excellent receiving antenna. Electric potentials (and current) are induced onto overhead lines from a number of sources, and these potentials ride on top of the normal line voltage. Such sources are:

- Radio signals from nearby transmitters
- Transients from lightning
- Transients and noise from customer sources
- Transients from customer and utility switching operations

All such sources add voltage to the normal line potential. Their sum can start, alter, change, and aggravate the operation of a microspark source in a bell insulator.

Furthermore, weather conditions can alter the operation of a microspark type of source. High humidity can cause one of all of the switches to close and terminate the operation of a source. Wind can alter the physical shape of any or all of the switches and alter the operation of a source.

At one time, it was believed that bells at the ends of short slack spans of conductors were more susceptible to microsparking than those at the ends of long tight spans. Field measurements have shown that this is not a reliable indicator of a source of noise.

Figure 34 illustrated the relationship between the line voltage waveform and the temporal structure of a typical microspark breakdown process.

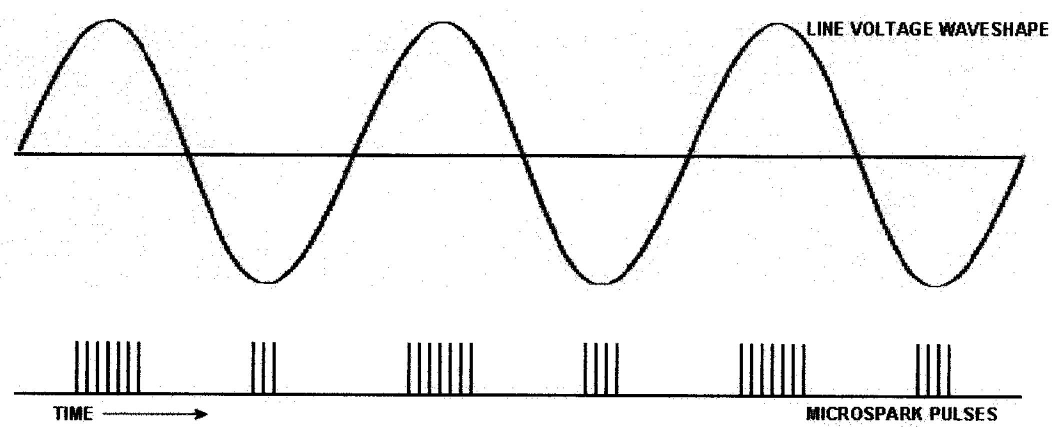


Figure 34 Sketch of Microspark Breakdown Process

The following steps summarize the multiple breakdown process of a microsparking source.

1. As the line voltage increases, the breakdown threshold of the thin layer of oxide is reached.
2. A large avalanche of current flows across the thin layer of oxide (7 to 9 A).
3. The potential across the oxide layer is equalized and the current flow stops. The breakdown is extinguished after a few microseconds of time.

4. The potential across the layer of oxide again increases to the breakdown point and another surge of current is generated. Each surge is equal in amplitude.
5. This process continues until the line voltage decreases to the point where it can no longer support the breakdown process.
6. This process is often, but not always, repeated on the opposite polarity of the line-voltage waveform. Sometimes it is repeated with different pulse patterns.

This process usually generates multiple microsparks during each voltage maximum. Each group contains about 1 to about 12 impulses. If only half of the voltage waveform produces a breakdown, the time interval between groups of impulses will be 16.6 ms for a 60-Hz power line and 20 ms for a 50-Hz power line. If the positive and negative portions of the line-voltage waveform both produce breakdowns of the layer of oxide, the time interval between groups of impulses will be 8.3 ms for a 60-Hz line and 10 ms for a 50-Hz power line. Each impulse causes a nearly equal impulse current to flow since the breakdown process is the same for all impulses. If the mechanism is very stable, the variation in pulse-to-pulse spacing with respect to voltage will be visible in the time-history view of the temporal structure of a succession of groups.

Still another factor must be considered to explain the full impact of radio noise from a microsparking source on a bell insulator. The impulse generated by each breakdown of the oxide layer is capacitively coupled onto the overhead power-line conductor by the relatively low RF impedance of capacitors C1 and C2. Impulse currents of 7 to 9 amperes in magnitude are injected onto the overhead line. These impulses create a strong electromagnetic field which efficiently radiates outward from the overhead line.

The radiation pattern of an electrically-long distribution-line conductor contains many nulls and lobes in accordance with the normal long-wire antenna-radiation principles. Since impulse current flowing in the antenna is similar to the levels of antenna current generated by a low- to medium-power transmitter, the amplitude of noise collected by a distant receiving site will be similar to that from such a transmitter.

3.1.3 Tie Wires

Tie wires are widely used to attach conductors to post, pin, spool, and saddle insulators. Bare conductors and bare tie wires are commonly used on US distribution lines. Insulated conductors are often found on the distribution lines of other countries, and sometimes they are found on short sections of US distribution lines. Unfortunately, from a noise standpoint, insulated conductors are becoming more popular in congested areas where a configuration called "compact line construction" is used. This construction is a problem because of the high electric fields resulting from the close spacing of the conductors.

Both bare and insulated tie wires can be found on both bare and insulated conductors. Bare preformed tie wires on bare conductors rarely produce radio noise since the tie wires are firmly bonded to the line conductors. This prevents the tie wire from assuming a potential different from the line conductor. The use of bare preformed tie wires is the preferred method of attaching bare line conductors to post or pin insulators.

Insulated tie wires on either an insulated conductor or a bare conductor can become a significant source of radio noise, and such construction, while standard for many electric utilities, should be discouraged. A number of examples of this kind of construction and the noise-source mechanism are provided, and Figure 35 shows an example of an insulated tie-wire holding an insulated conductor to a pin insulator.

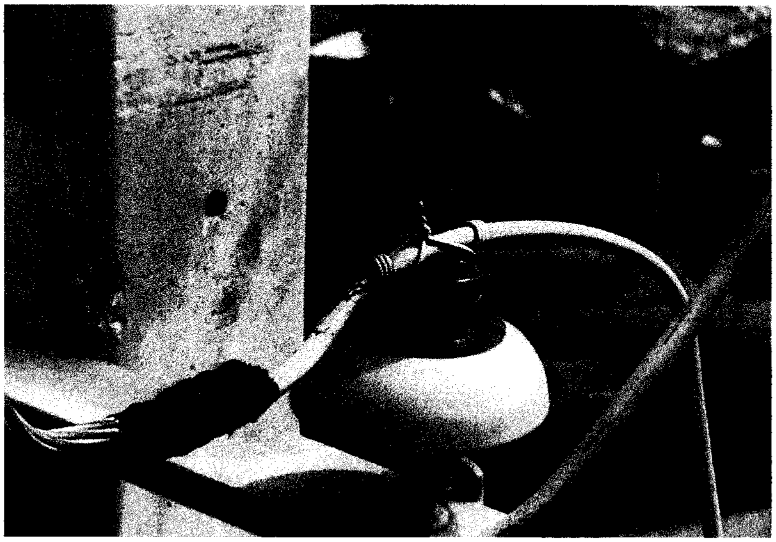


Figure 35 Insulated Tie Wire on an Insulated Conductor

Figure 36 shows example of a small gage insulated tie wire holding a bare conductor to a pin insulator.

Figure 36 Insulated Tie Wire on a Bare Conductor

The capacitance between the conductor and the tie wire shown in Figures 35 and 36 is about 30 to 50 pf. This is sufficient to charge the tie wire to a potential nearly equal to the line-to-ground potential but of the opposite polarity. While the insulation between the conductor and the tie wire will usually tolerate the normal potential difference, other factors must be considered. The insulation on both the tie wire and the conductor deteriorates with exposure and age. In addition, overhead conductors carry significant levels of radio signals, transients from utility switching actions, transients from customer operations, radio noise from customers, and transients from lightning and atmospheric electricity. These sources all have high-frequency components, up to tens of megahertz that add directly to the normal line potential. The normal potential difference between the conductor and the tie wire, along with the added potential provided by transients and other sources, is often sufficient to cause failure of the insulation on the conductor and tie wire. The insulation of even a new or replacement tie wire can quickly fail from the added potential difference caused by such sources; especially that from a nearby lightning strike. Once the insulation is penetrated with a spark and weakened, the normal potential difference between the line conductor and the tie wire is often sufficient to cause the breakdown process to continue.

The insulation breakdown typically occurs at sharp bends in the tie wires and at the end of the tie wires. The electric field between the line conductor and a tie wire is maximum at such locations. Once a breakdown occurs, the insulation properties are decreased, and a continuous sparking can take place between the two conductors. Each spark induces an impulse of current into the overhead conductors. These current impulses have high-frequency spectral components that radiate from the overhead lines.

The minimum length of the sparking path between the line conductor and the tie wire is the thickness of the insulation. Once started, the sparking path can expand in length and follow the path of damaged insulation. Tie wire sparking paths up to ½ inch in length, and sometimes longer, are common. Multiple failures on a single tie wire can occur. Figure 37 shows an example of the breakdown of an insulated tie wire. Severe deterioration of the insulation occurred from sparking.

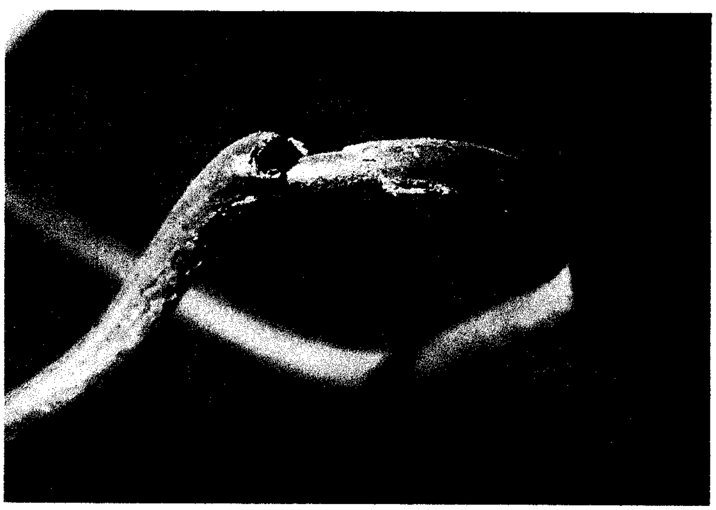


Figure 37 Insulation Failure at a Bend in a Tie Wire

Figure 38 shows the deterioration of insulation from sparking at and near the end of a tie wire where the potential between the tie wire and the line conductor is high at the high-frequency spectral components of the sparking process. This is similar to the high potential that exists at the ends of a dipole antenna. Note that the insulation has been trimmed from the end of the tie wire by sparking as well as causing damage to the insulation at several places a few inches from the end of the tie wire.

Figure 38 Insulation Failure at the End of a Tie Wire

In addition to the above sparking problem, deteriorated tie-wire insulation can sometimes allow the tie-wire conductor to come into contact, or near contact, with the line conductor. If a layer of oxide forms between the tie-wire conductor and the line conductor, or a very small spacing exists between them, micro sparking can also occur. Both sparking and micro-sparking sources can exist on a damaged tie wire, sometimes simultaneously.

3.1.4 Lightning Arresters

A new lightning arrester seldom generates radio noise, however all lightning arresters, old and new, can be damaged by lightning or other severe line transients. When damaged, lightning arresters can be sources of severe radio noise.

Figure 39 shows a lightning-damaged arrester installed on one phase of a three-phase distribution line. The top of the arrester is connected to the line conductor and the bottom end at one time was connected to a ground wire. Note that the bottom connection to ground has been blown free from the arrester by lightning, a key indication that the internal components of the arrester probably have been damaged. The bottom connection of many arresters has been designed to separate from the body of the arrester as shown in the photograph. In addition the bottom connection of some arresters will purposely turn brown when damaged as shown in the photograph.

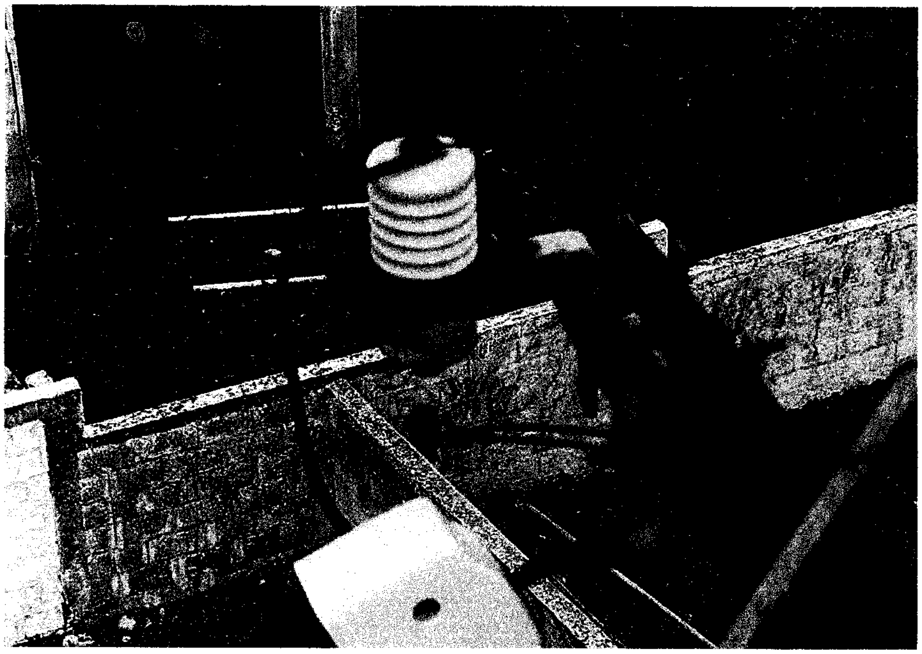


Figure 39 Example of a Damaged Lightning Arrester

The radio noise is caused by the failure of the insulating gap or semiconductor material inside the arrester. This results in micro sparking and sometimes sparking inside the arrester. A single spark source can occur inside an arrester or several microsparking sources can occur. Multiple sources of microsparks often produce groups of overlapping impulses during the maximum part of the line-voltage waveform.

Any lightning arrester with either indicator of damage should be immediately replaced or as a minimum be disconnected from the overhead-line conductor. It is a good practice to locate all lightning arresters within line of sight of the uppermost part of the antennas of a receiving site on a map and visually inspect each arrester after each severe lightning storm as well as check damaged arresters for radio noise.

3.1.5 Loose and Unbonded Hardware

Loose and unbonded hardware is often a source of radio noise. This includes a large number of potential sources including loose bolts, loose insulator-support pins, loose crossarm braces, inadequately separated conducting objects, loose staples on ground conductors, debris on the line, and leakage paths caused by insulation degradation or failure.

Sparking can occur between any two conducting objects located within the near-zone electric field of a line conductor or which can be excited by an electrical leakage path. Sparking between two adjacent pieces of metal can be avoided by maintaining a spacing of at least 1½ inches or more or by solidly bonding closer-spaced items.

Figure 40 shows an example of a hardware source. In this case an insulator support bolt protruded through the crossarm and touched the crossarm brace. During wet weather the bolt-to-crossarm spacing opened and caused a small gap to exist. Sparking across this gap caused severe radio noise to a receiving site located 2 km from the source.

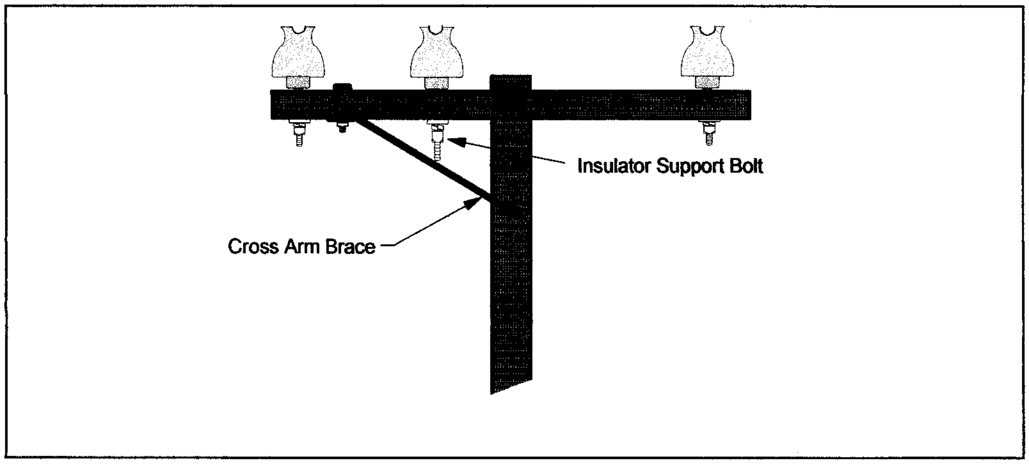


Figure 40 Hardware Source, Example 1

Figure 41 shows a source where a ground wire used to bond metal components together passed over the metal brace supporting a plastic crossarm. A small spark occurred between the ground wire and the brace. This induced noise current into the ground wire and other nearby objects. The length of the ground wire was sufficient to make it an efficient radiator of the noise.

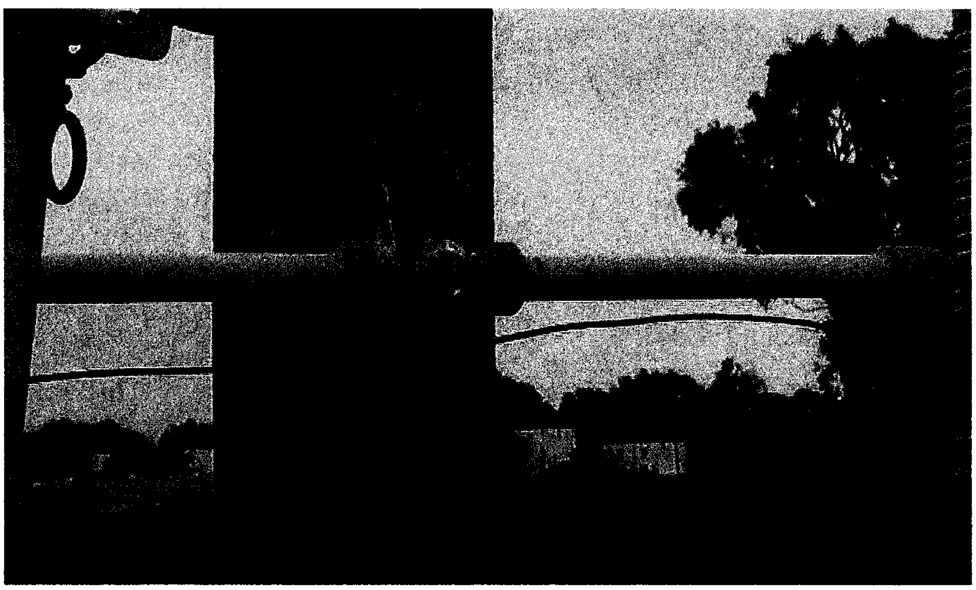


Figure 41 Hardware Source, Example 2